Preliminary System Architecture Description

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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 CDR.

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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
AD02	ngVLA System Architecture Modeling Plan	020.10.20.00.00-0003
AD03	ngVLA Product Breakdown Structure	020.10.40.00.00-0001
AD04	ngVLA N-squared matrix	020.10.10.05.00-0001
AD05	Antenna Electronics Block Diagrams: Sheet1 – Top Level Sheet2 – Front End Enclosure Sheet3 – Auxiliary Enclosure Sheet4 – WVR enclosure Sheet5 – Cryogenic / EEC enclosure Sheet8 – Electronics Rack Sheet13 – SA501 Sheet14 – SA 502 Sheet15 – L501	020.30.00.00.00-0005
AD06	ngVLA Observing Modes Framework	020.10.05.05.00-0005
AD07	ngVLA System Conceptual Design Report	020.10.20.00.00-0001
AD08	ngVLA L1 System Requirements	020.10.15.10.00-0003
AD09	ngVLA Stakeholder Requirements	020.10.15.01.00-0011
AD10	ngVLA System Concept Options and Trade-offs	020.10.25.00.00-0005

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
RD02	Antenna to Antenna Electronics ICD	020.10.40.05.00-0011
RD03	ngVLA Calibration Plan Overview	020.10.25.00.00-0006
RD04	ngVLA Monitoring and Control Concept	020.50.25.00.00-0002
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

Ref. No.	Document Title	Document Number
RD10	Observing Modes Framework	020.10.05.05.00-0005
RD11	ngVLA Data Processing Concept	020.50.55.00.00-0001
RD12	A Notional Reference Observing Program	020.10.15.05.10-0001
RD13	Amdahl GM (1967) Validity of the single-processor approach to achieve large scale computing capabilities. AFIPS Joint Spring Conference Proceedings 30 (Atlantic 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
RD16	Designing an ngVLA Dynamic Scheduler	ngVLA Comp. Memo #6

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.

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.

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 processing facility where mixed-use of the facility resources (power, cooling, rack space, etc.) is expected by the correlator, control and monitoring, science processing 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:
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.
System PDR: A complete functional system functional architecture should be defined for the System PDR, including the full scope as defined above.
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 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 System Architecture Modeling Plan [AD02] defines the purpose and scope of the architectural model in more detail.

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.

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 Product decomposition (PBS) 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.

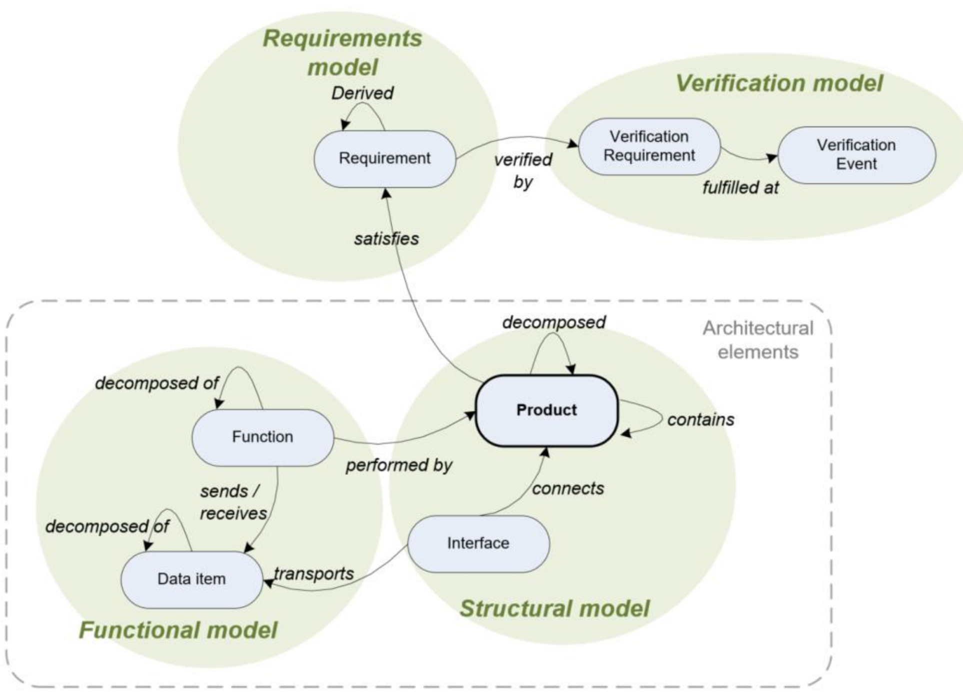

Figure 1: Representation of the system architecture in the system model

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:

A	B	C	D	E	F	G	H	I	J	L	M	N	P	Q	S
ngVLA Product Breakdown Structure (PBS)								Configuration Item Number 020._	Code	Requirements level	Architecture layer	N^2 interfacing Item	Responsible IPT / WP	Location	**CDR Baseline**
1	2	3	4	5	6	7	<-- PBS level								.
	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. Therefore, a relational database tool is required to represent and manage the PBS. 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 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 are likely needed for the receivers (e.g. faster scanning capabilities; improved gain stability).
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 transmits 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.

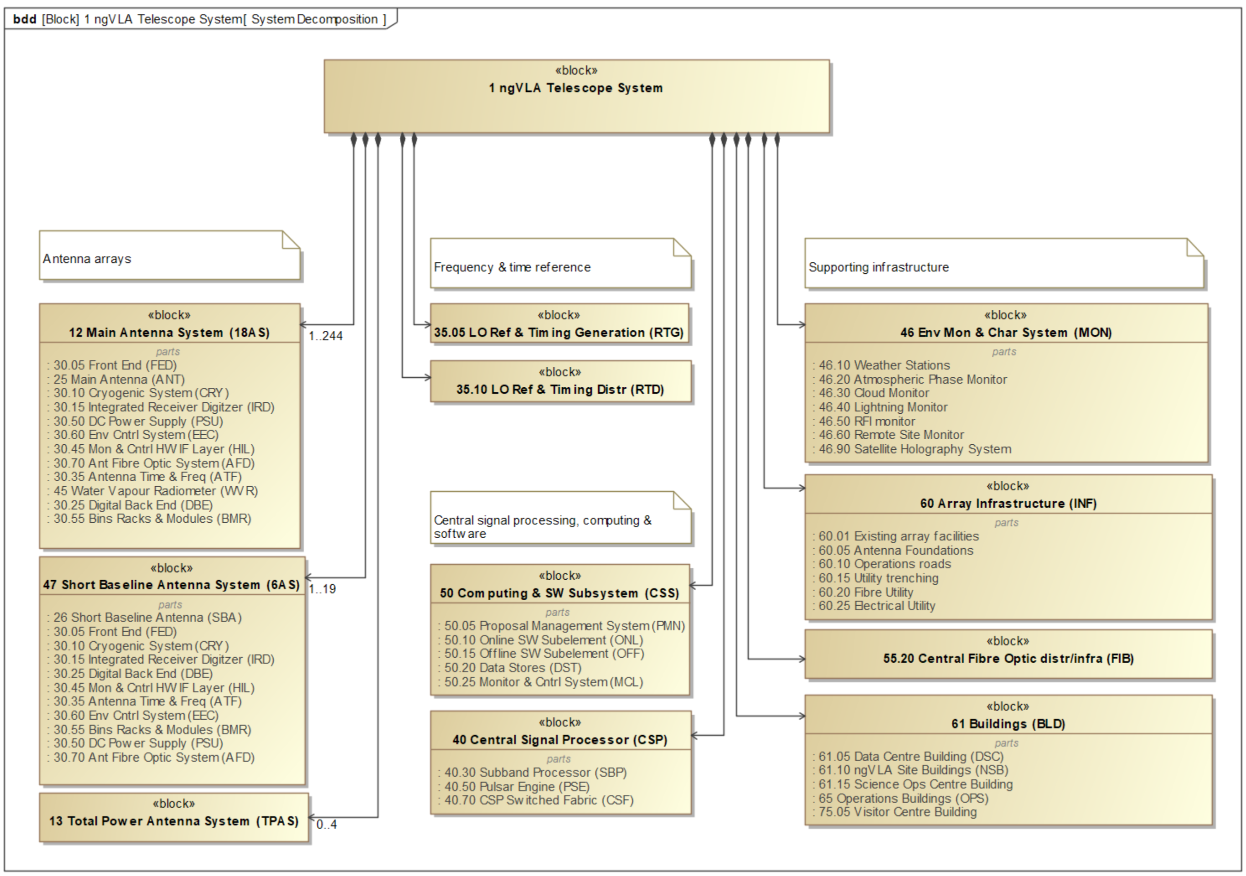

Figure 3: Product breakdown structure of Telescope System

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, yoke, 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: to distinguish between the Main Antenna System, which includes all the electronics, and the Main Antenna, which 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).

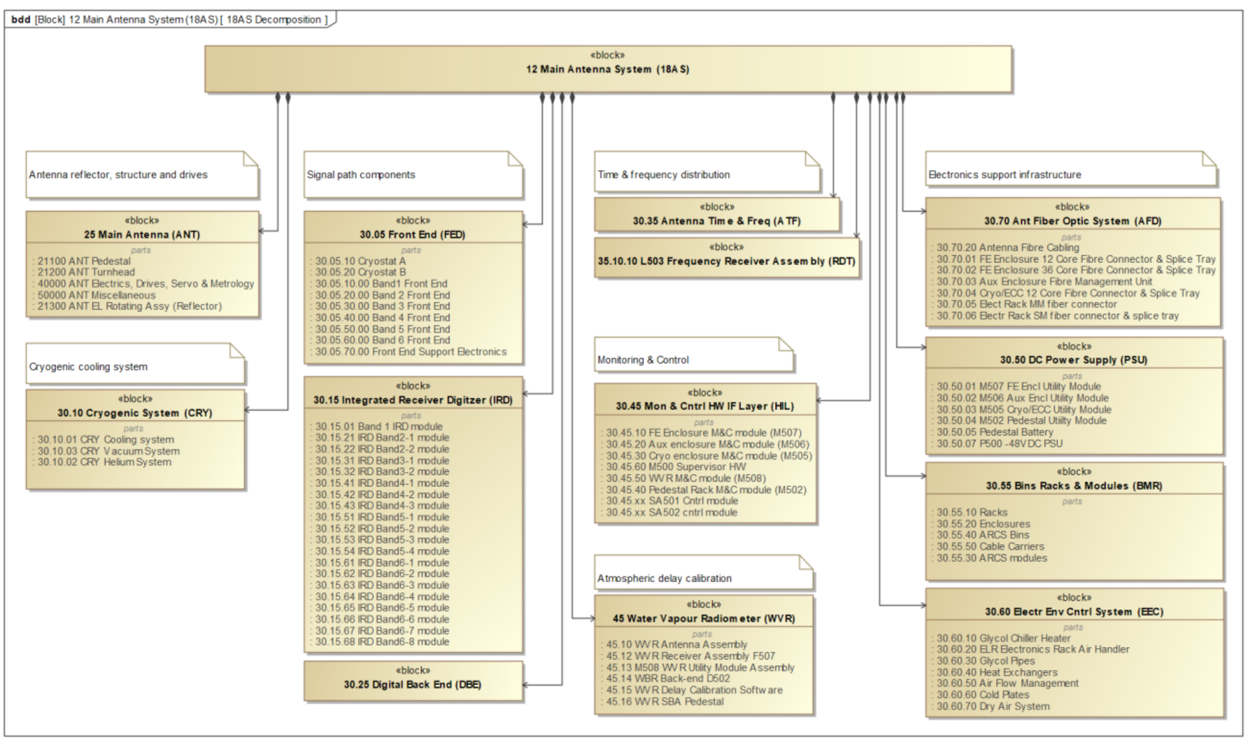

Figure 4: Product Breakdown Structure of Main Antenna System

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.

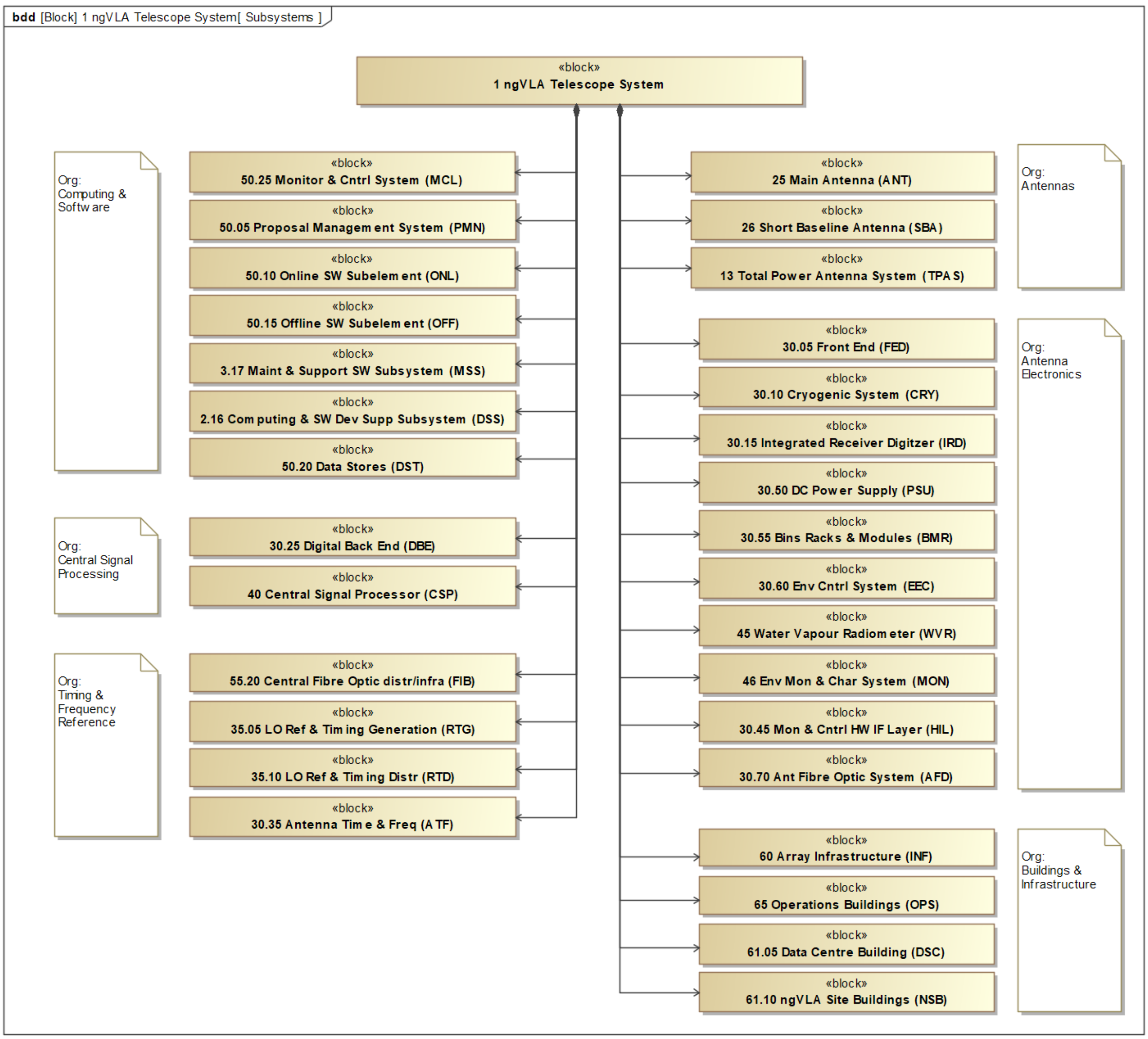

Figure 5: ngVLA Subsystems

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		*0130*	*0131*		*0132*	*0133*	*0134*	*0135*			*0136*	0030				0031				S								TBC
	SBA	*0032*	*0033*		*0034*	*0035*	*0036*	*0021*			*0037*	0038				0039				S								TBC
		FED	0012	0004	*0014*	*0040*	0017			*0015*	*0041*					~~0042~~				S								~~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*					~~0027~~		S		S				TBC			0128	0028
									MON	*0071*		0072				*0073*		S		S								
										HIL	*0074*					0075				S				~~0076~~		0129	*0077*	*0078*
											AFD									S			*0079*	*0080*				*0081*
												INF	0082		0083	0084				S			0085					
													OPS			*0086*		~~0087~~		S			*0088*					
														DSC		*TBC*	*0089*		*0090*	*0091*	*0092*	*0093*	*0094*					
															NSB	*0095*		*0096*		S			*0097*	*TBC*	*0098*	*0099*	*0100*	
																MCL		0101		0102	S	*0103*		*0104*	0105	0106	*0107*	~~0108~~
																	PMN	0109	0110		S	*0111*						
																		ONL	0112		S	*0113*		S	0114	S		
																			OFF		S	*0115*	0116					
																				MSS	S	*0117*		S	S	S	S	S
																					DSS	*0118*						
																						DST						
																							FIB	TBC	0119		0120	
																								DBE	0121		0122	
																									CSP	0123		
																										RTG	0124	
																											RTD	0125
																												ATF

Table 1: System interface identification

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 the physical configuration of the monitoring and control interfaces from the MCL subsystem to the Antenna Electronics subsystems, via the HIL subsystem. Next lower level interfaces are identified, based on the N² 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 in the System Architecture Model to represent their physical, functional and data structures, as illustrated in an example in the Appendix B section 7.

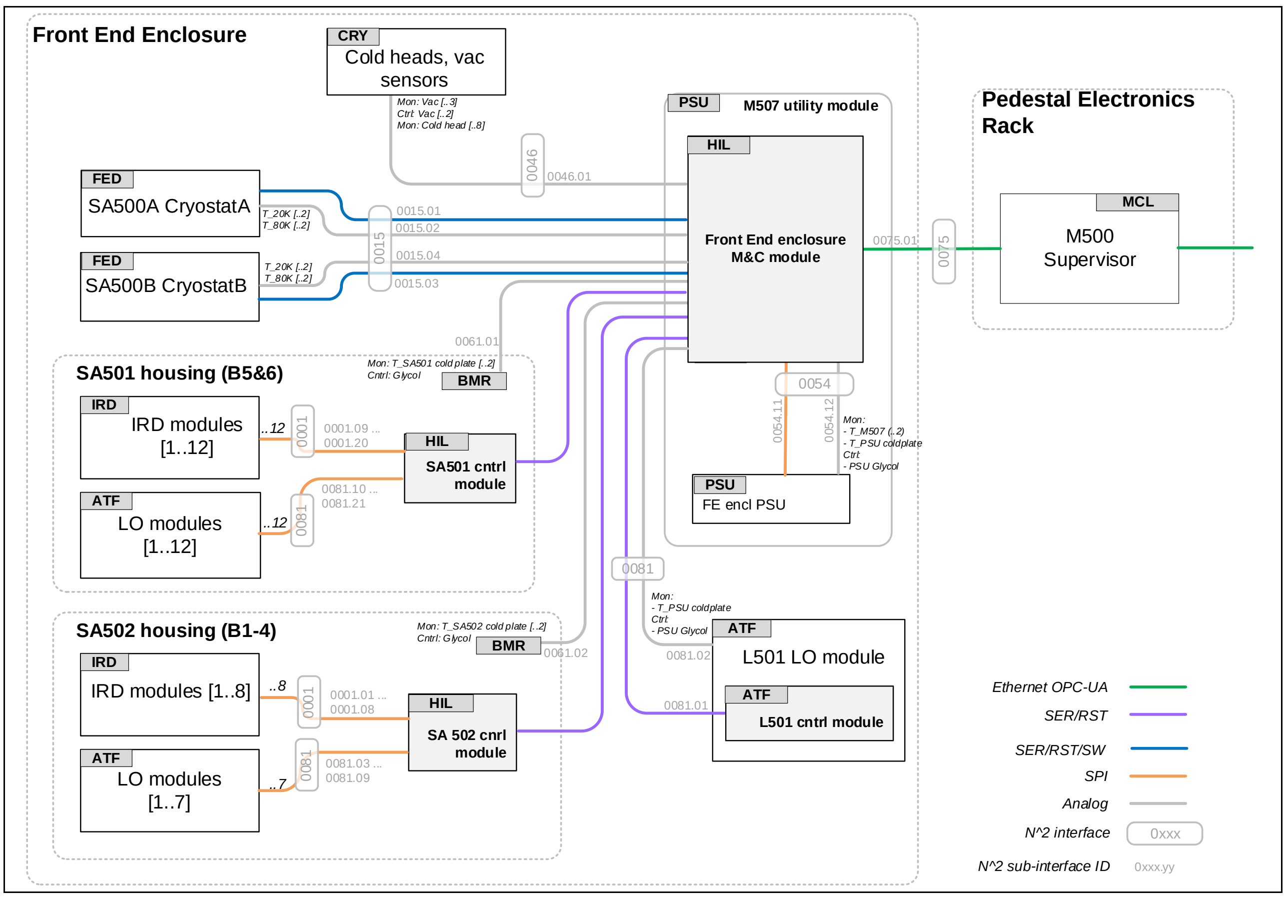

Figure 6: Front-end control and monitoring interfaces

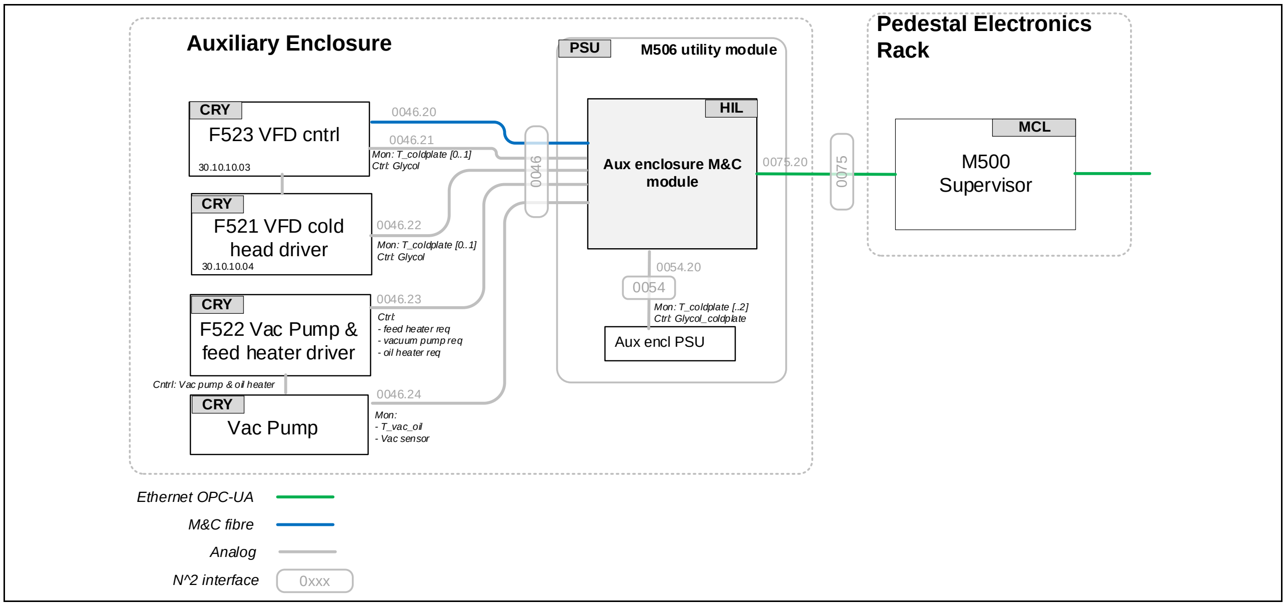

Figure 7: Auxiliary enclosure control and monitoring interfaces

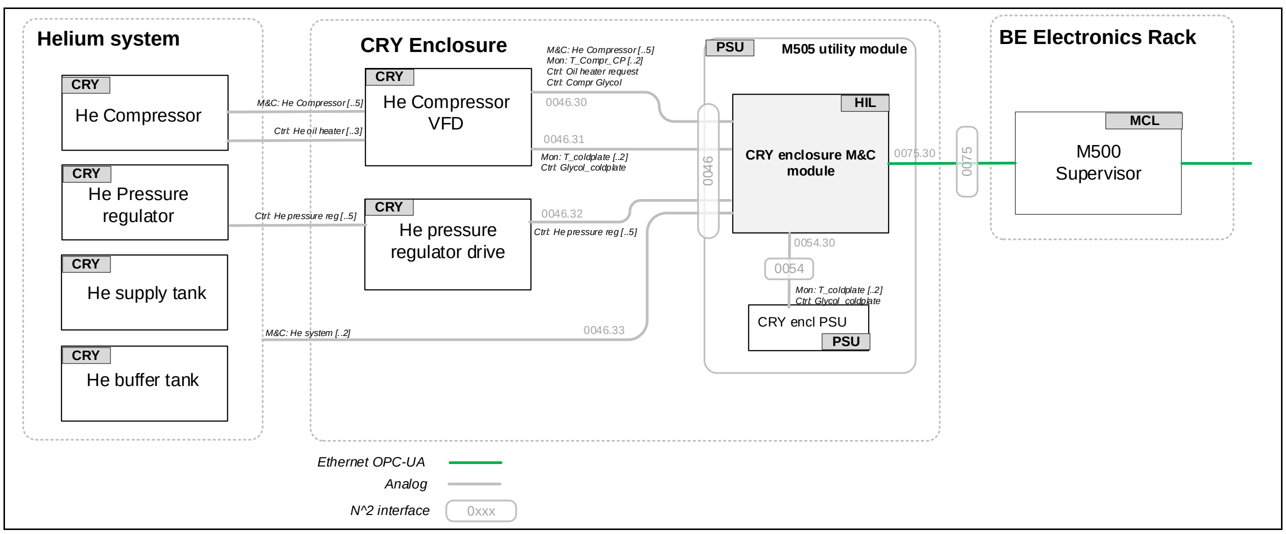

Figure 8: Cryogenics enclosure control and monitoring interfaces

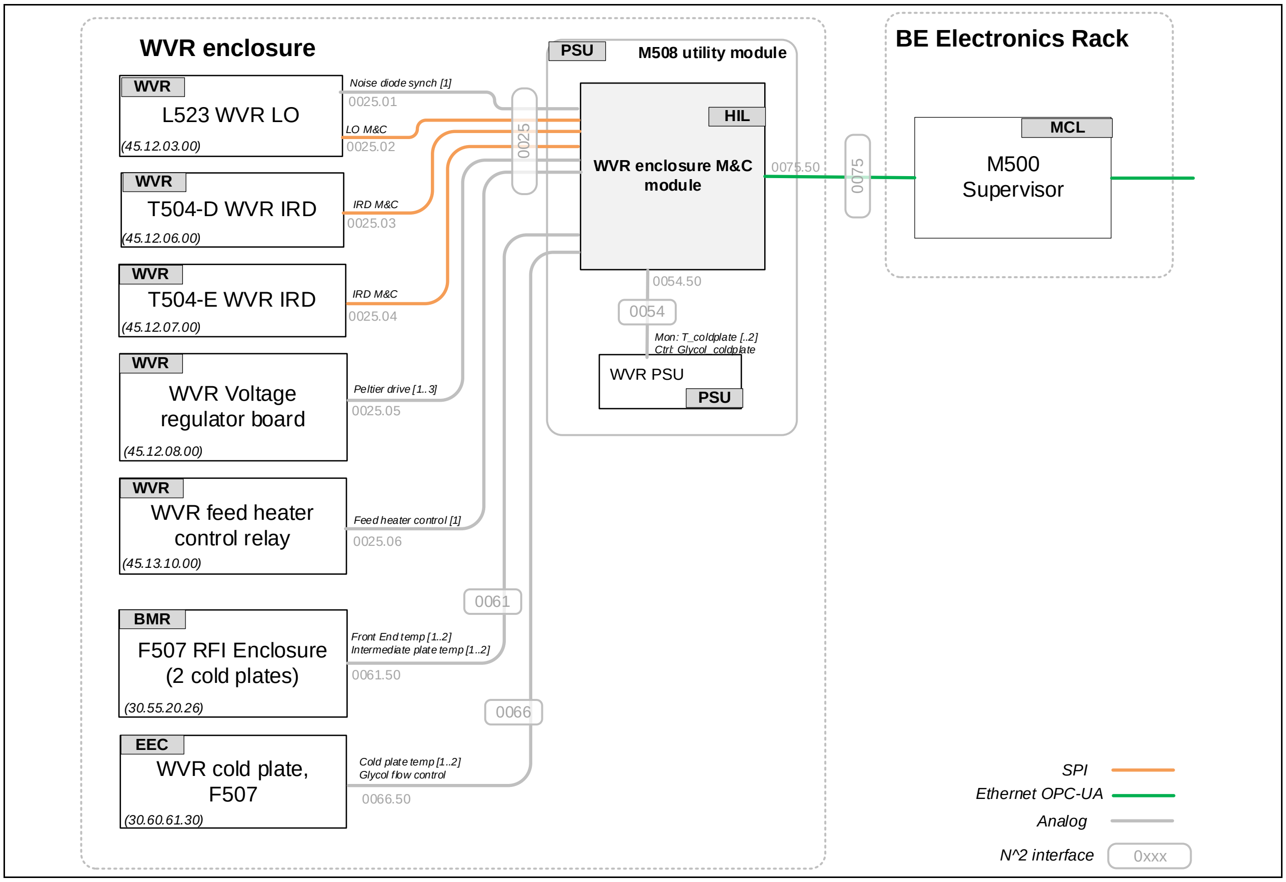

Figure 9: WVR Control and Monitoring Interfaces

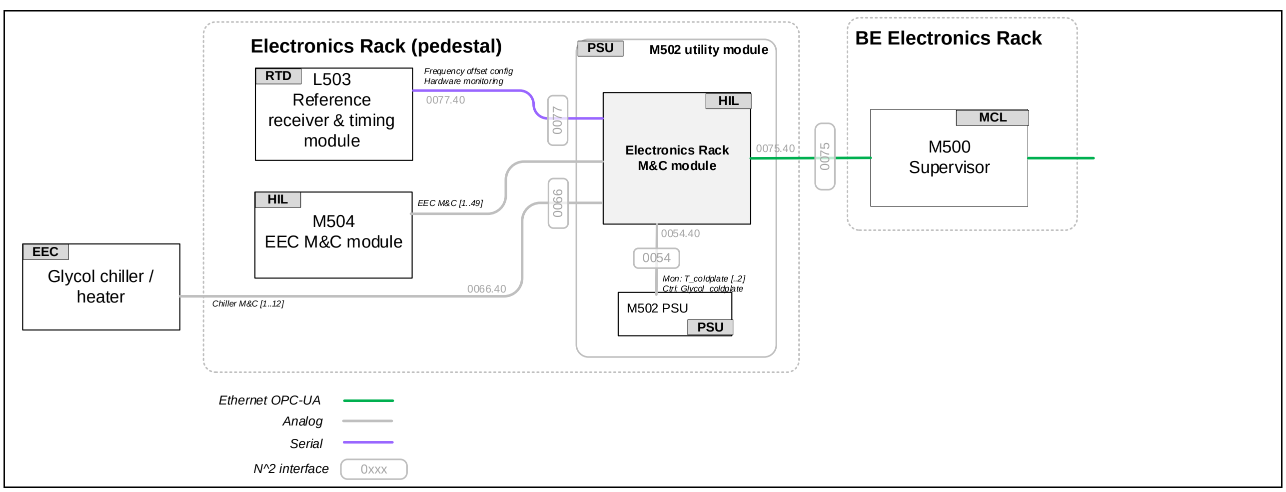

Figure 10: Electronics Rack control and monitoring interfaces

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 and feed indexer system. It 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 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 yoke 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.
e) Miscellaneous items include supporting equipment needed for the installation, integration and verification of the Main Antenna.

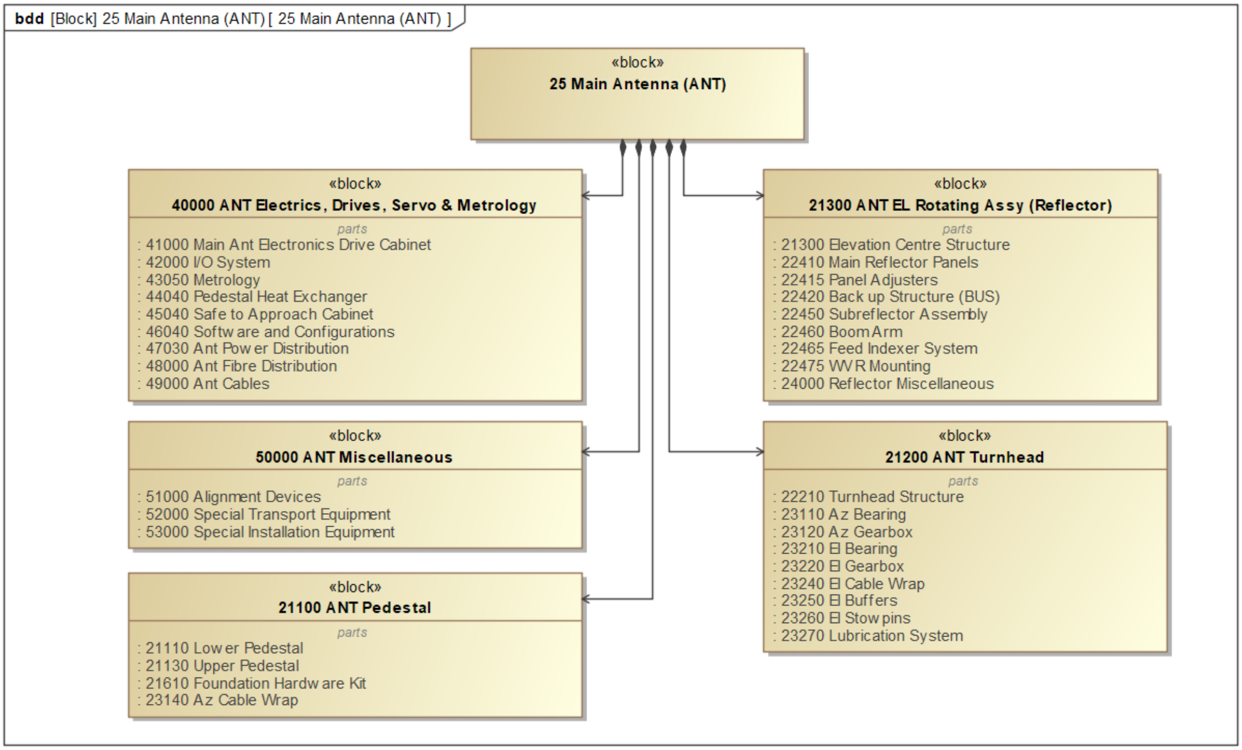

Figure 11: Main Antenna decomposition

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.
c) Monitoring and control (MCL) for the monitoring and control of the antenna and the provision of a time reference via the M&C network.

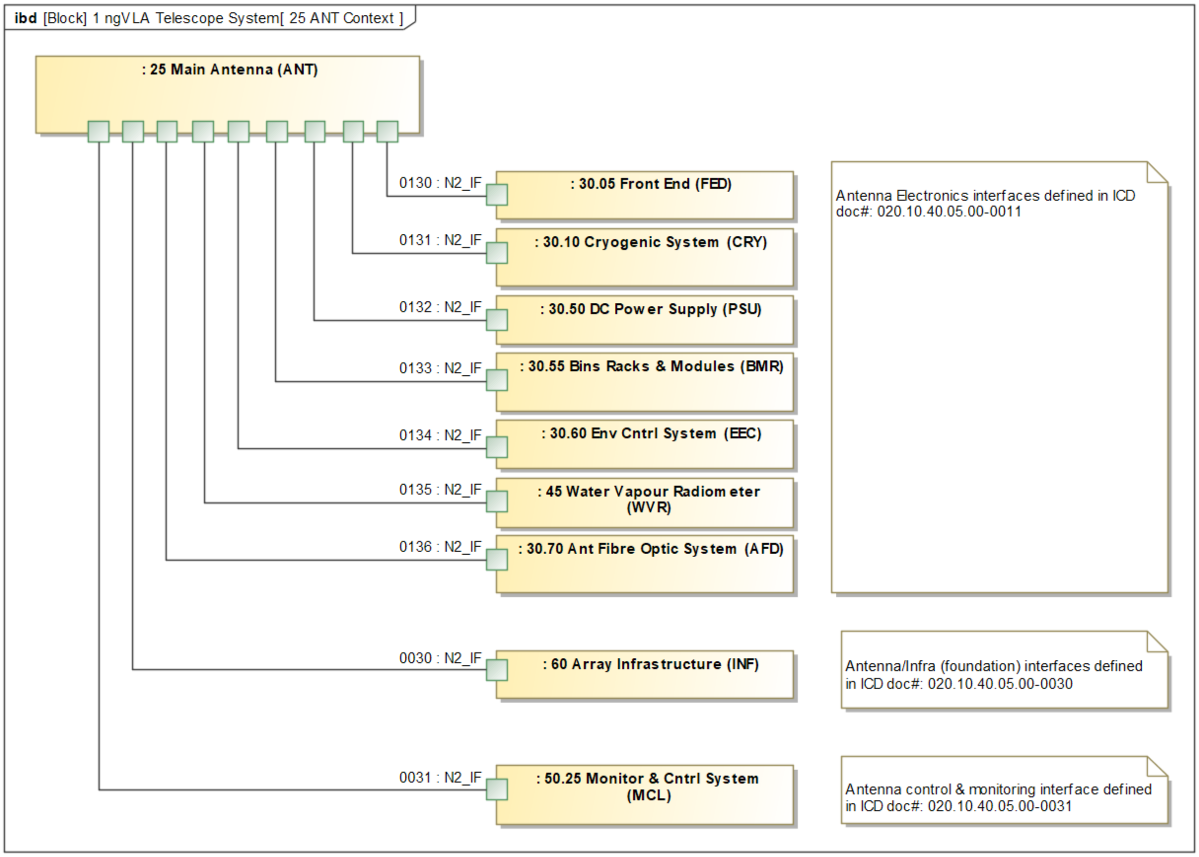

Figure 12: Main Antenna external interfaces

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 will 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.

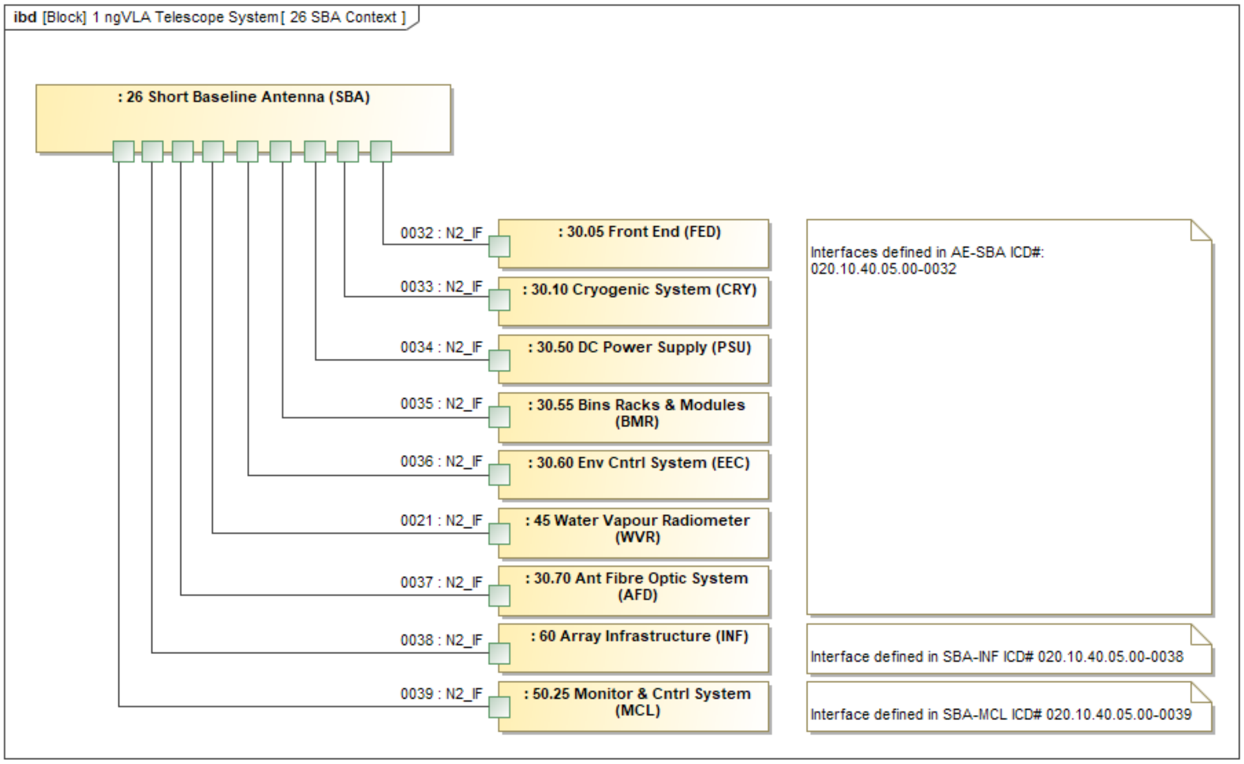

Figure 13: Short Baseline Antenna external interfaces

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, allowing for the switching between bands and focal adjustment. The product decomposition of the Front End is shown in Figure 14.

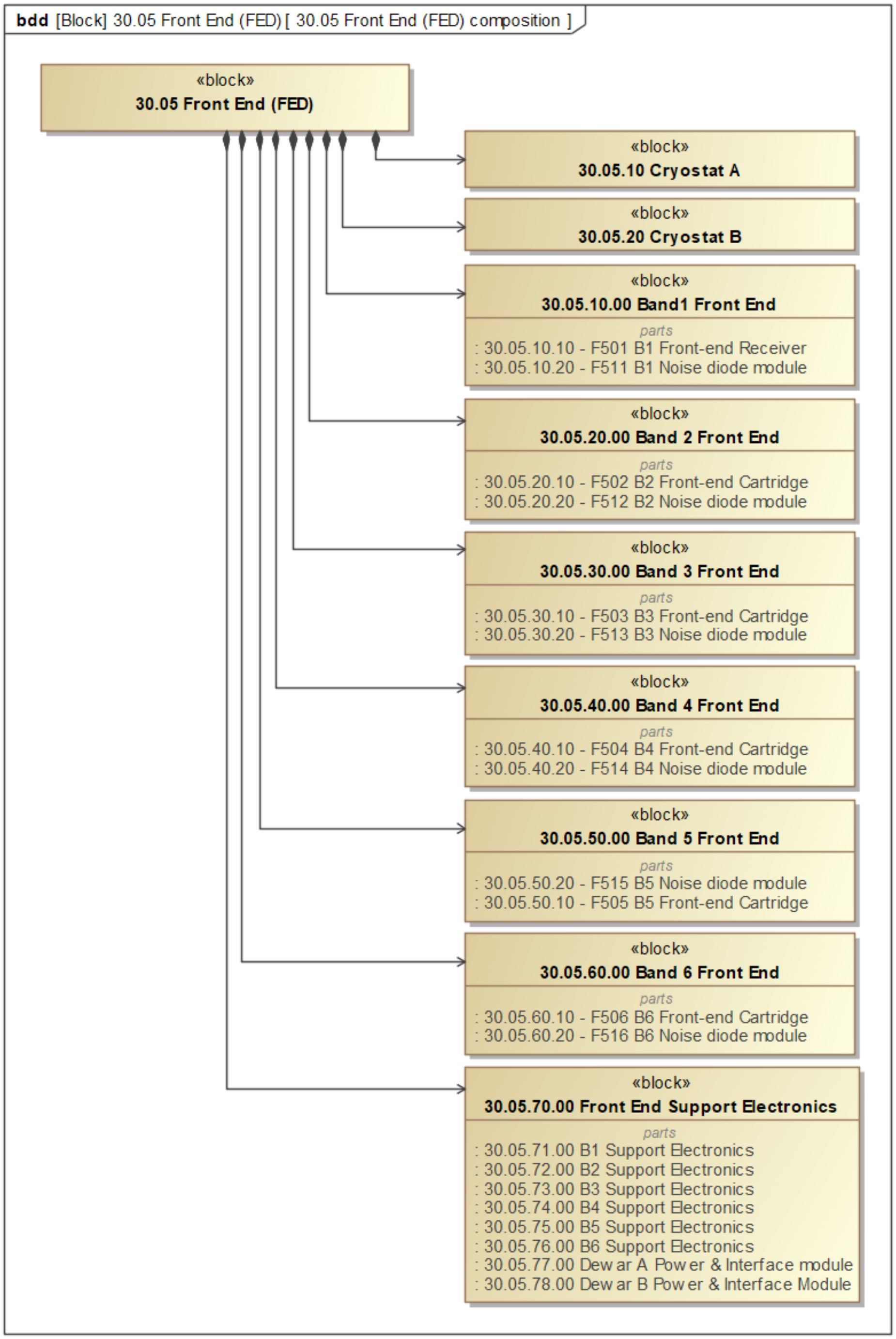

Figure 14: Front-end Decomposition

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.

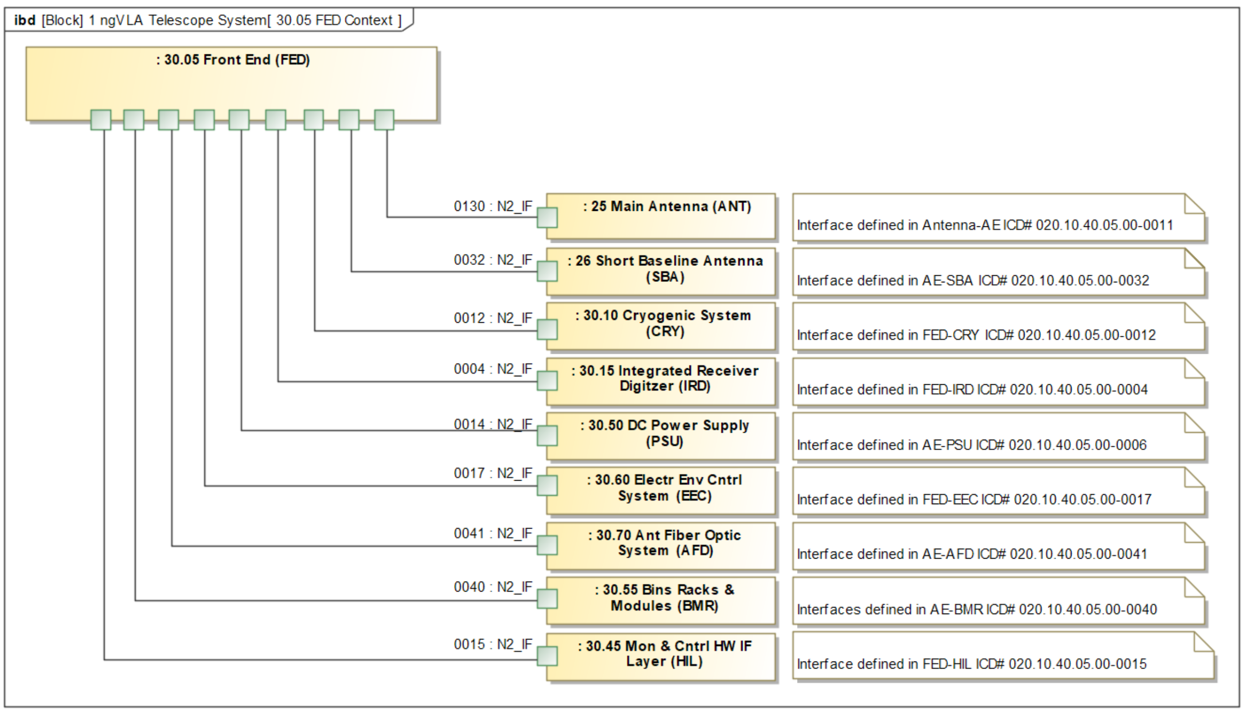

Figure 15: Front-end Context

4.6.4 Antenna Electronics: Cryogenic Subsystem (CRY)

The purpose of the cryogenic subsystem is to cool the Front-End electronics to a very 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 is shown in Figure 16 below.

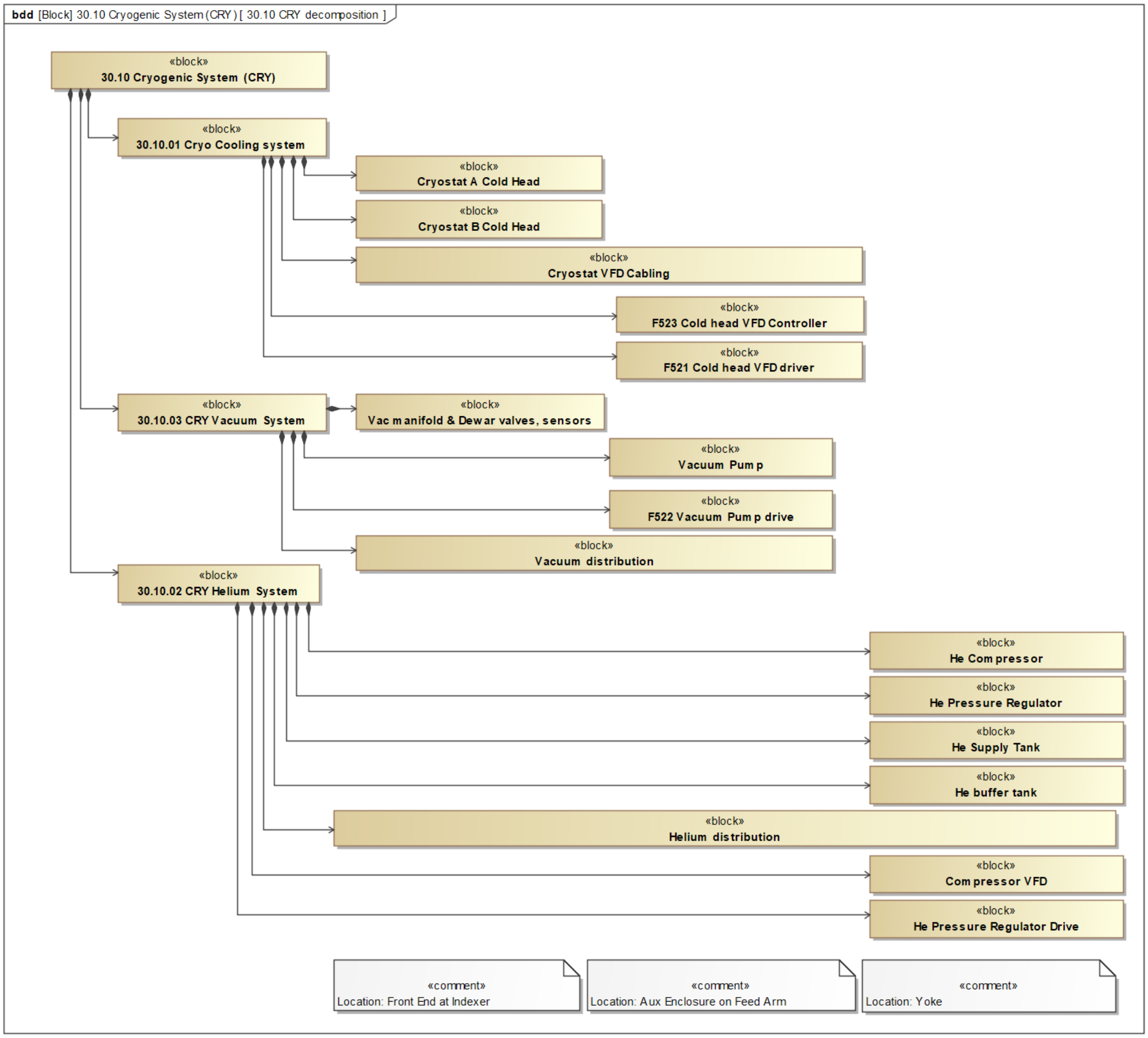

Figure 16: Cryogenic Subsystem decomposition and location

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 yoke 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.

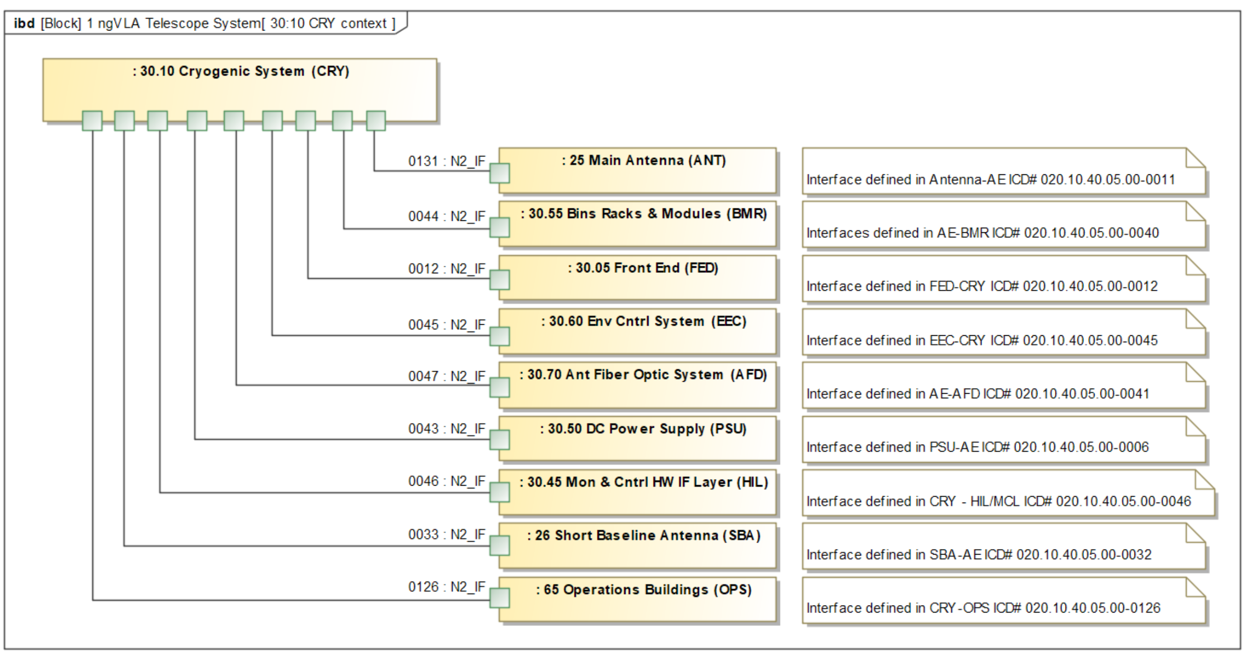

Figure 17: Cryogenic Subsystem external interfaces

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.

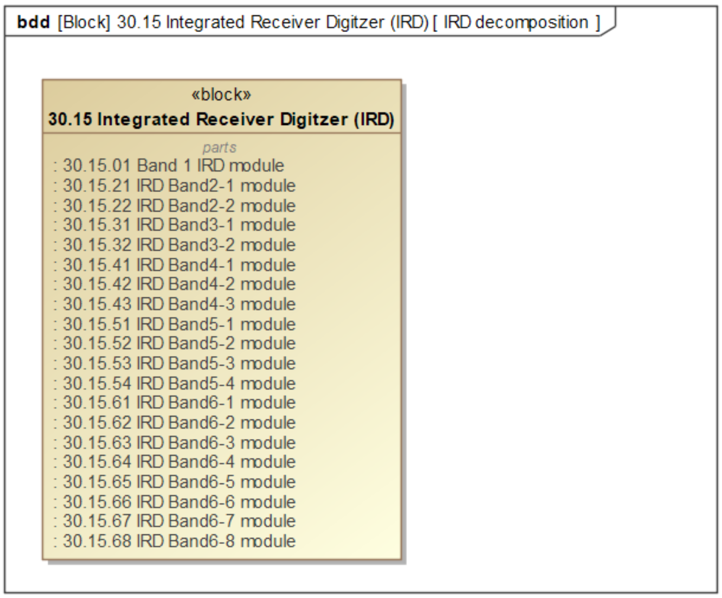

Figure 18: IRD decomposition

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.

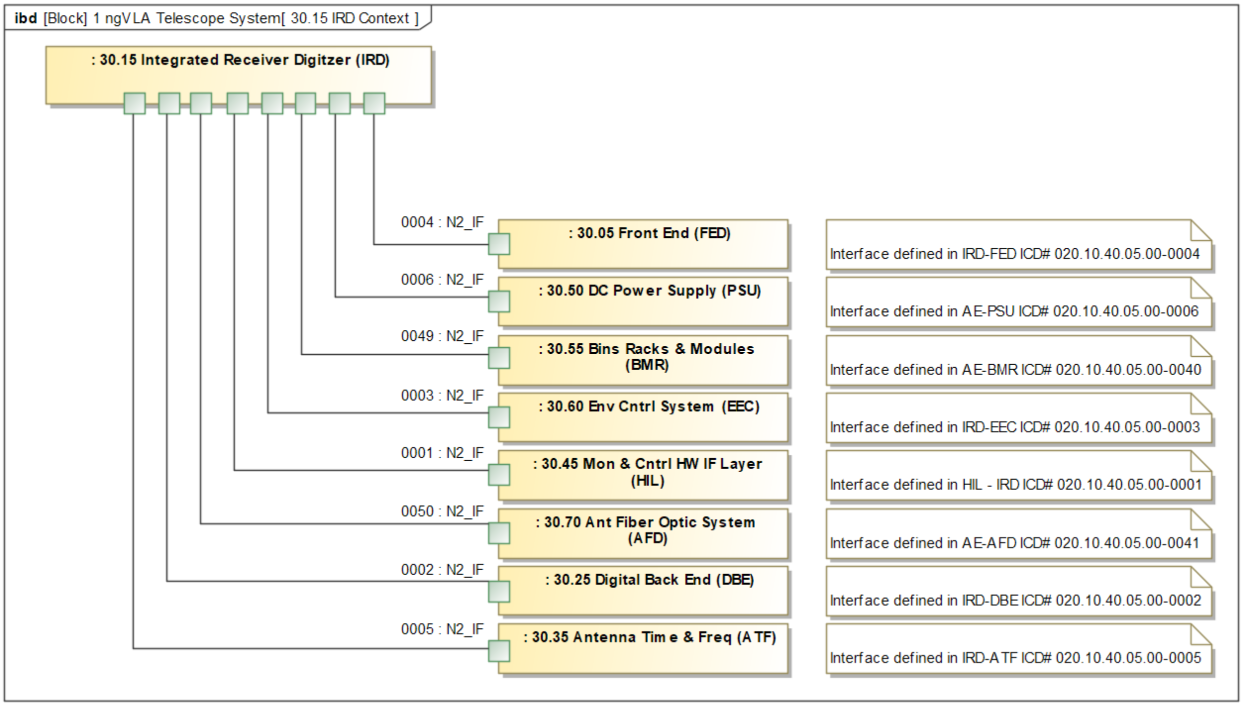

Figure 19: IRD external interfaces

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.

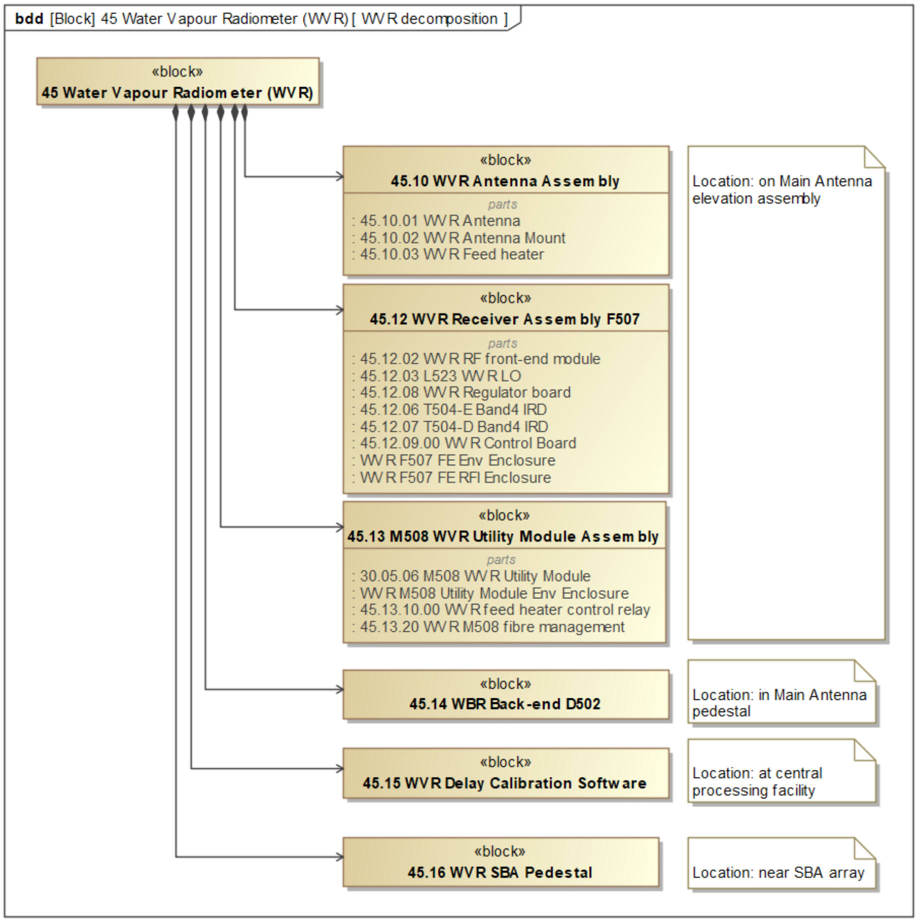

Figure 20: WVR decomposition

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.

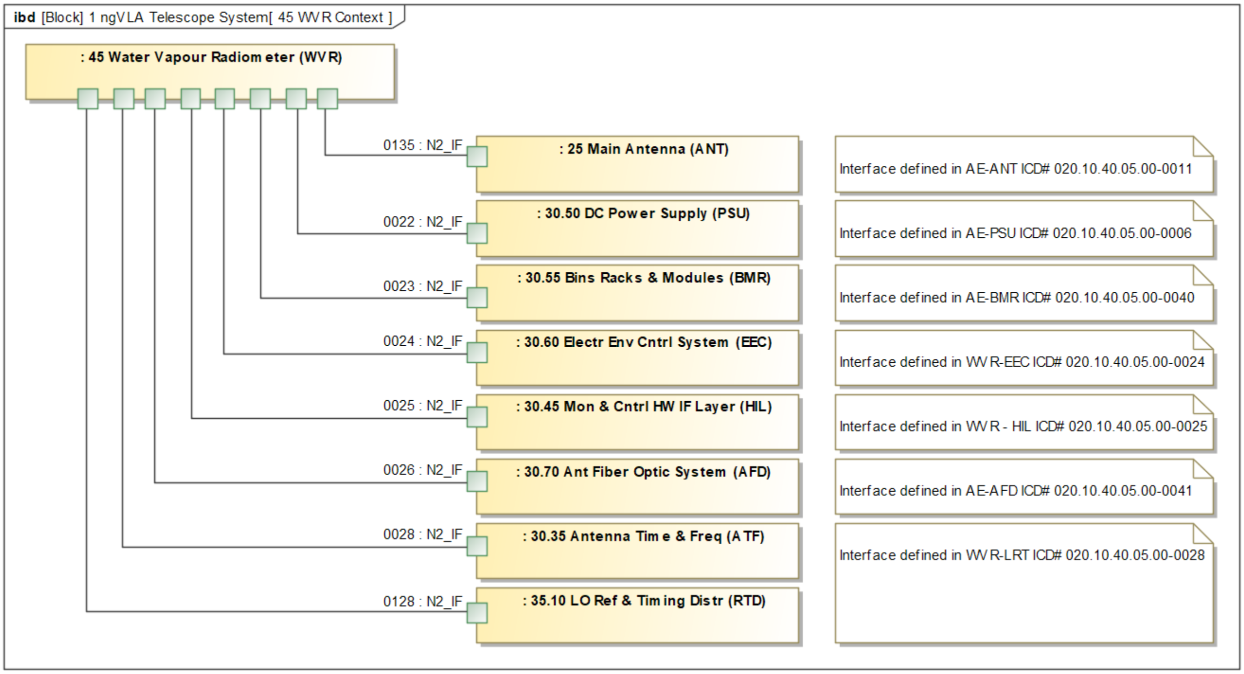

Figure 21: WVR external interfaces

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.

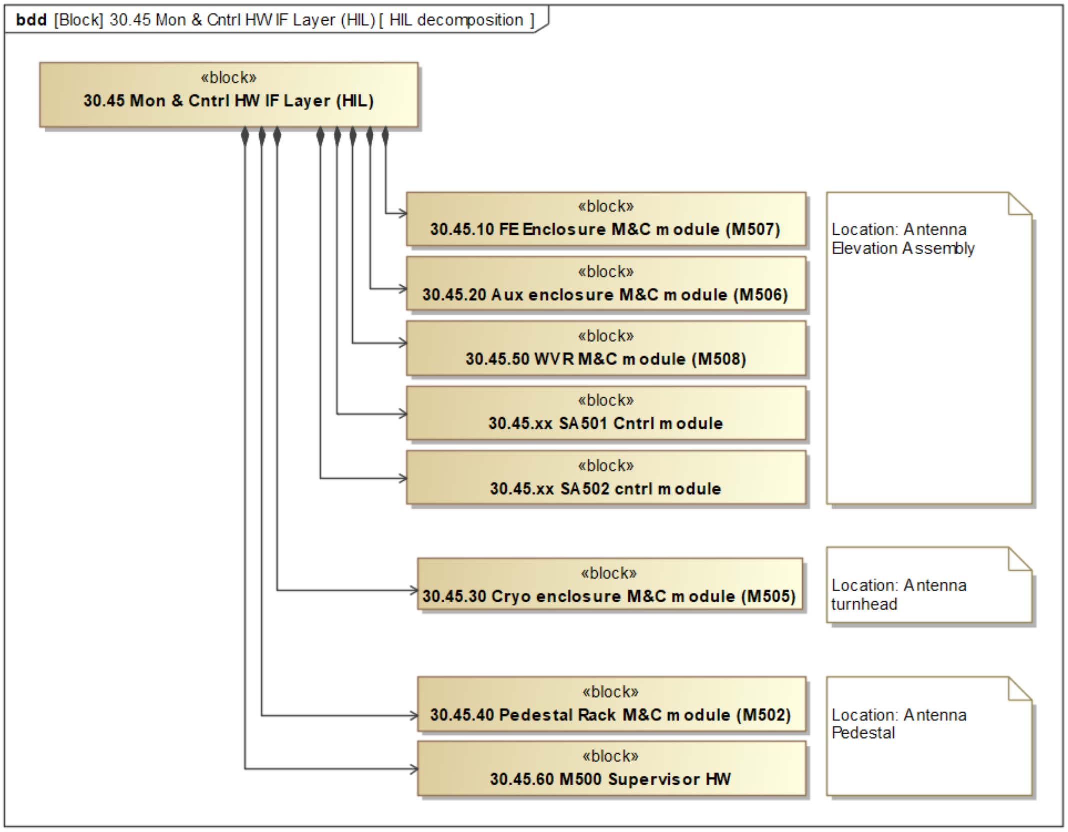

Figure 22: HIL decomposition

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.

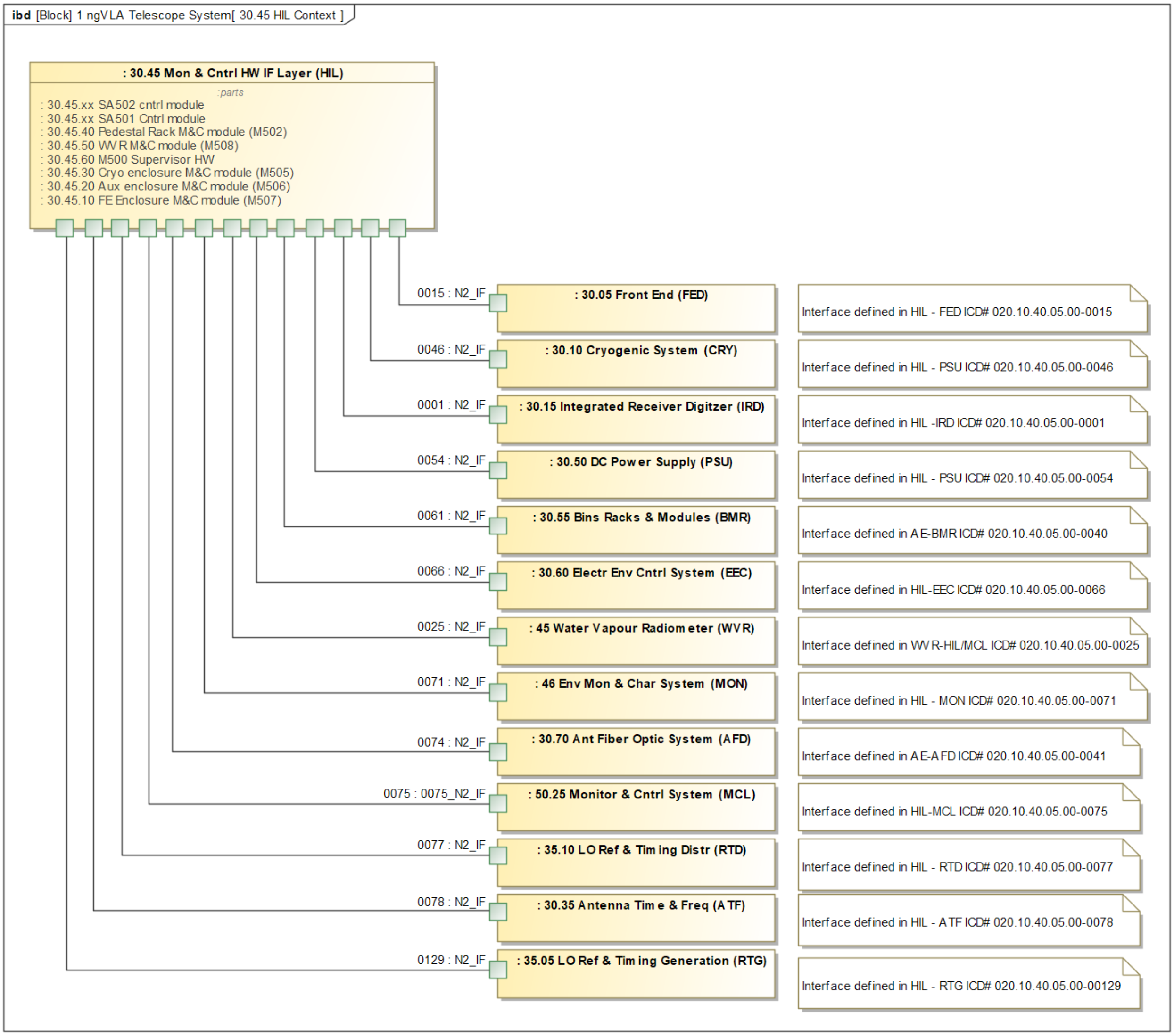

Figure 23: HIL external interfaces

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.

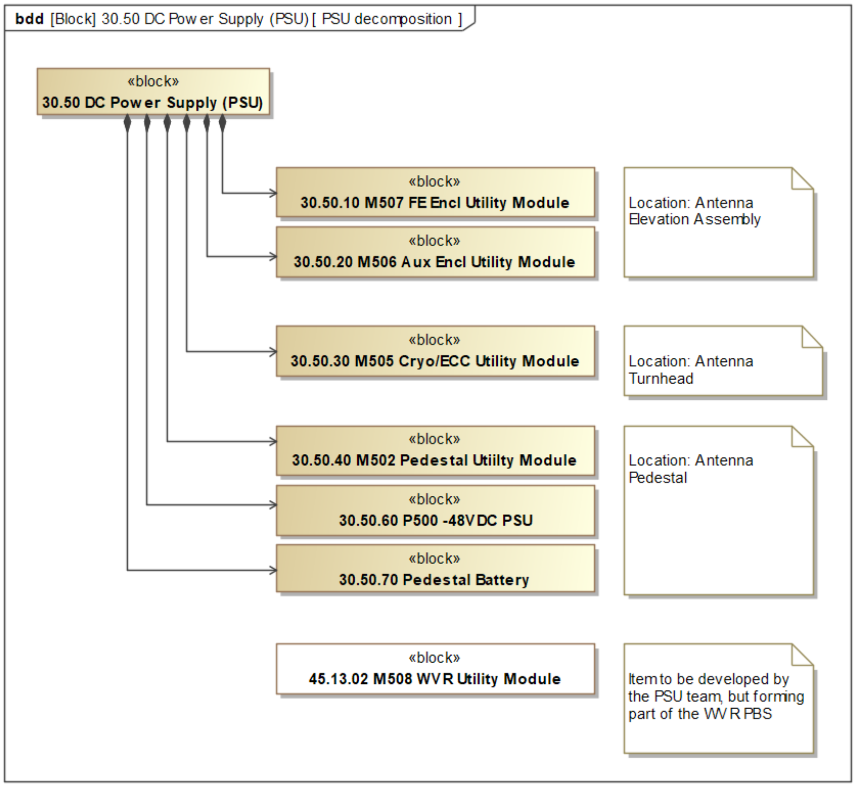

Figure 24: PSU decomposition

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.

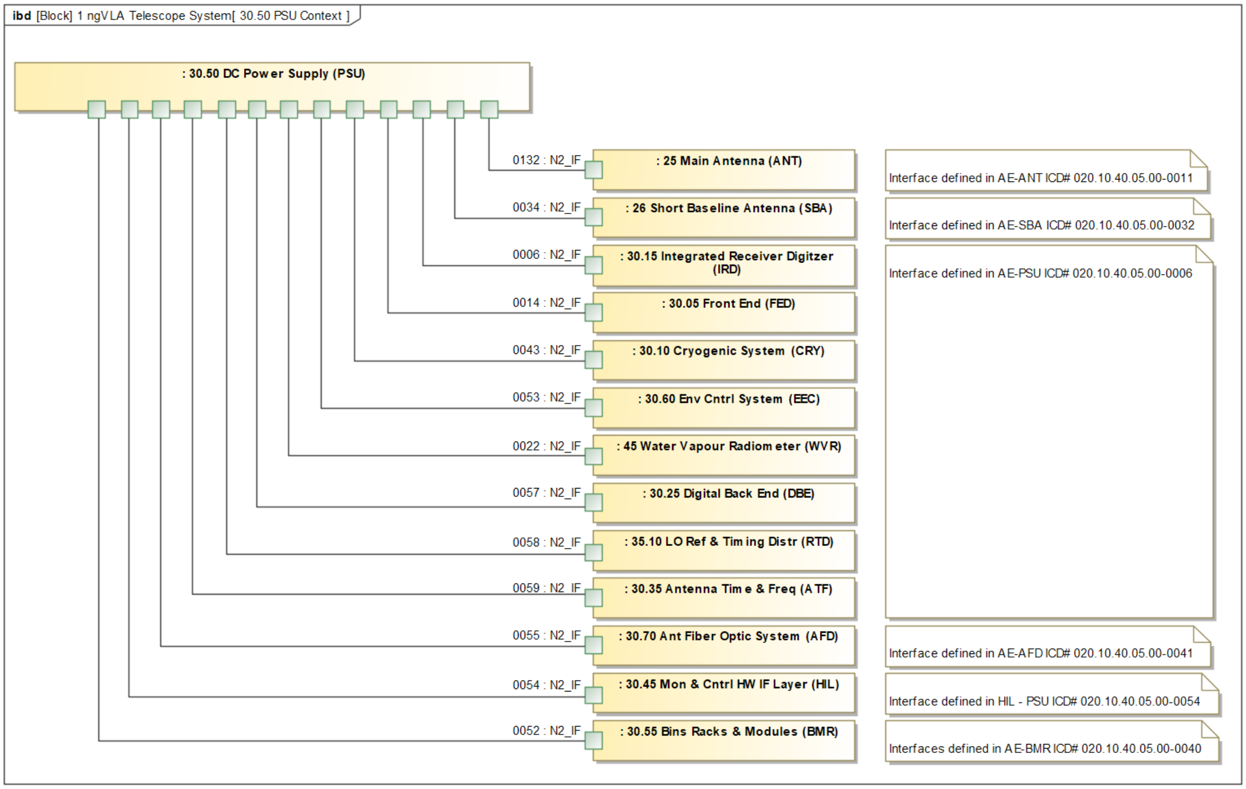

Figure 25: PSU external interfaces

4.6.9 Antenna Electronics: Bins, Racks and Modudules (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).

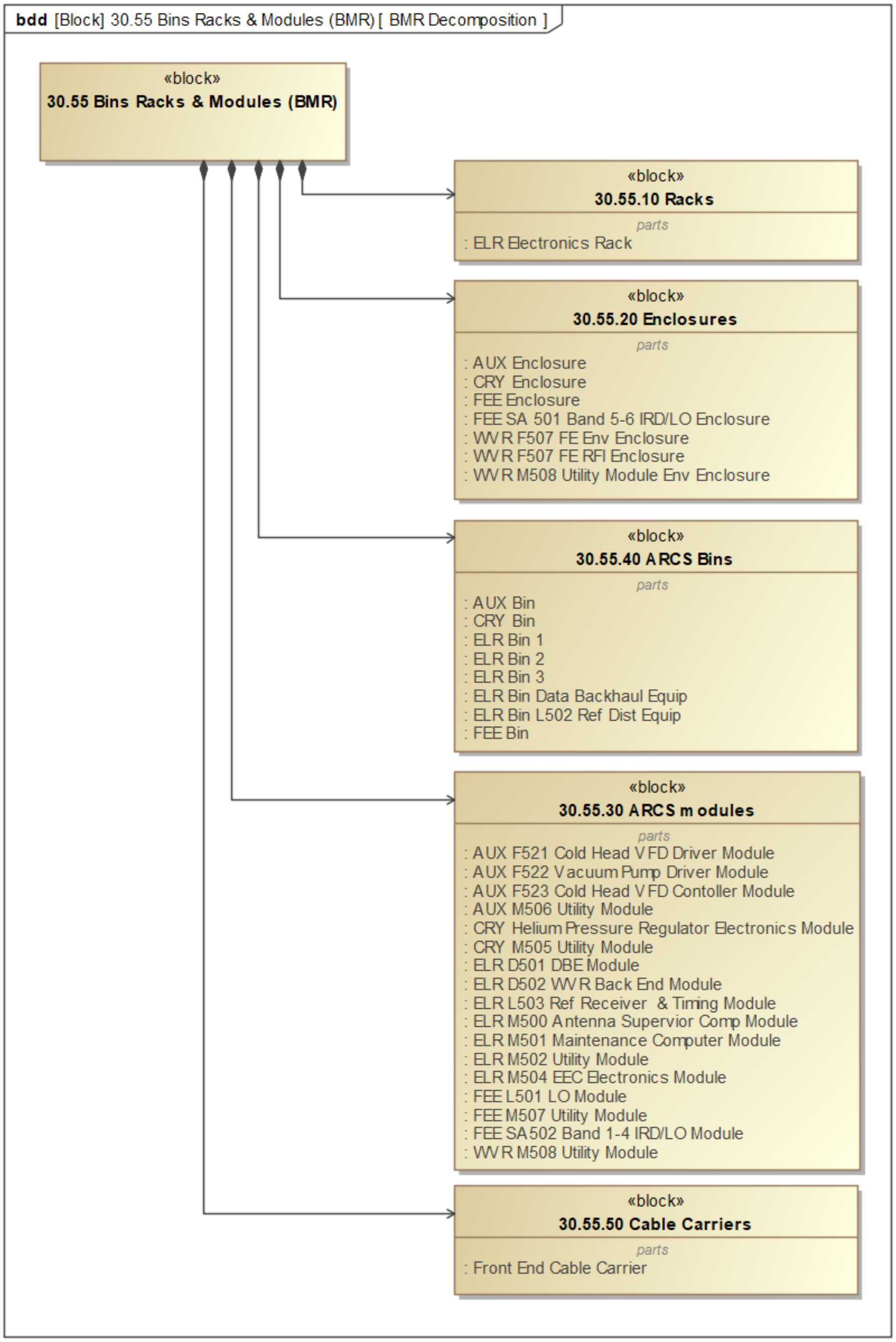

Figure 26: BMR decomposition

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).

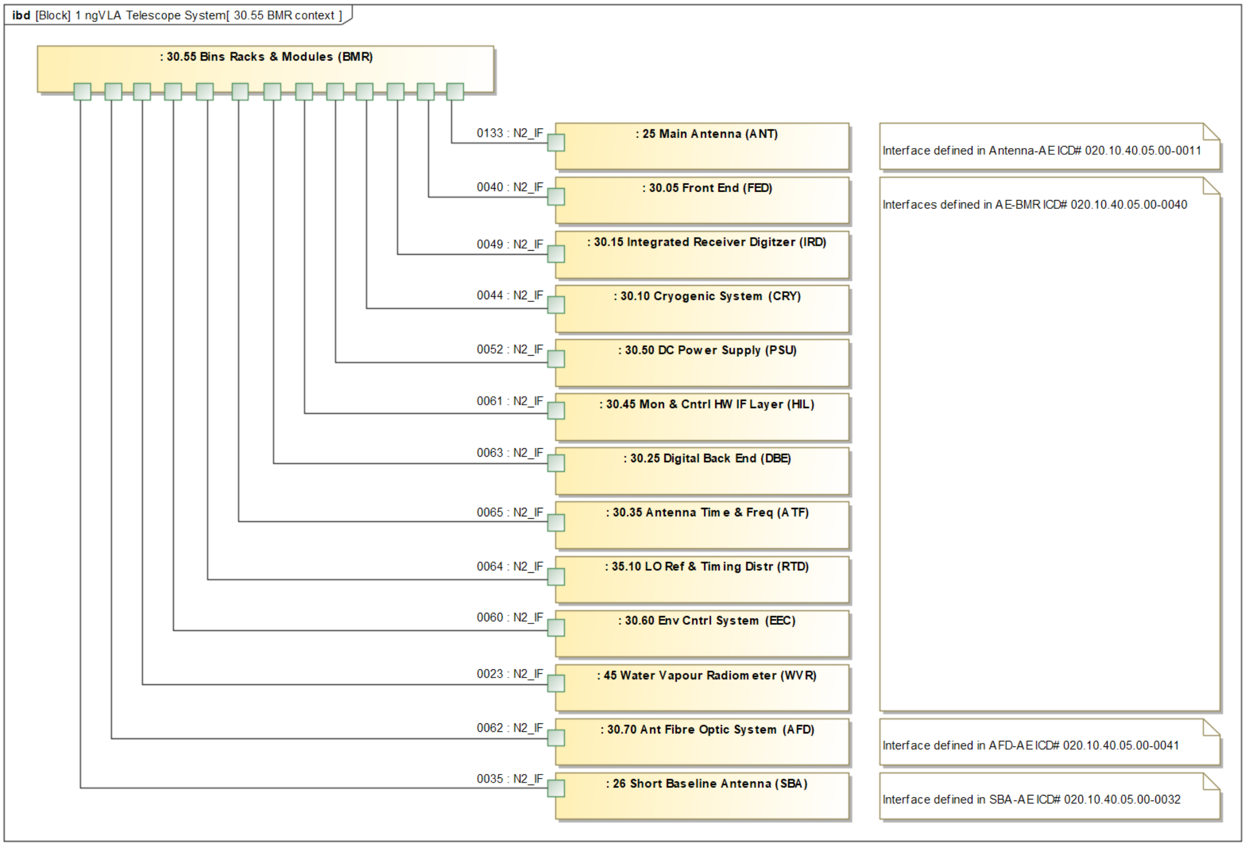

Figure 27: BMR external interfaces

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 shelter 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.

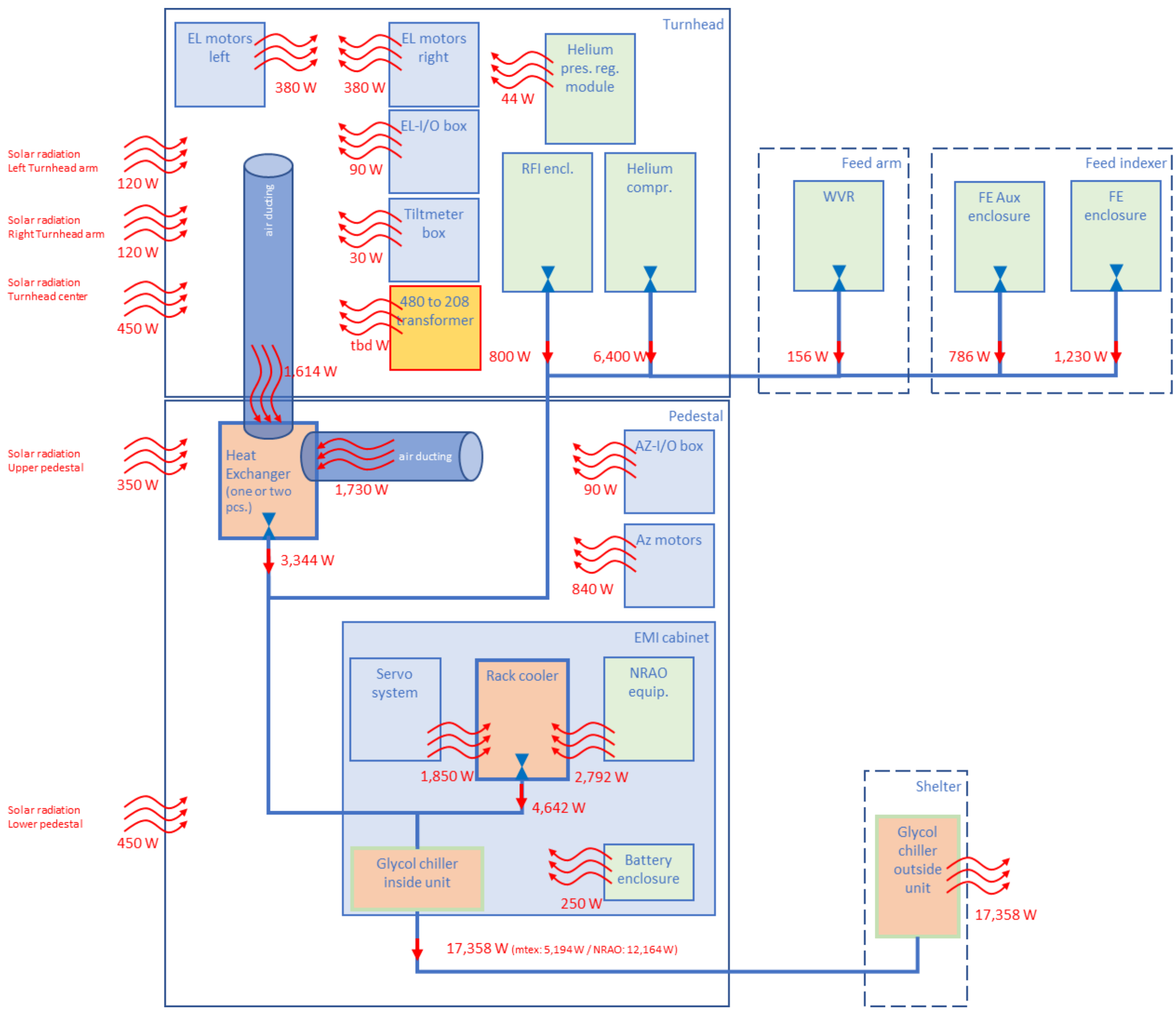

Figure 28: Overview of the Antenna Environmental Control System

The product breakdown structure of the EEC is shown in Figure 29 below. A more detailed breakdown of components can be found in the PBS.

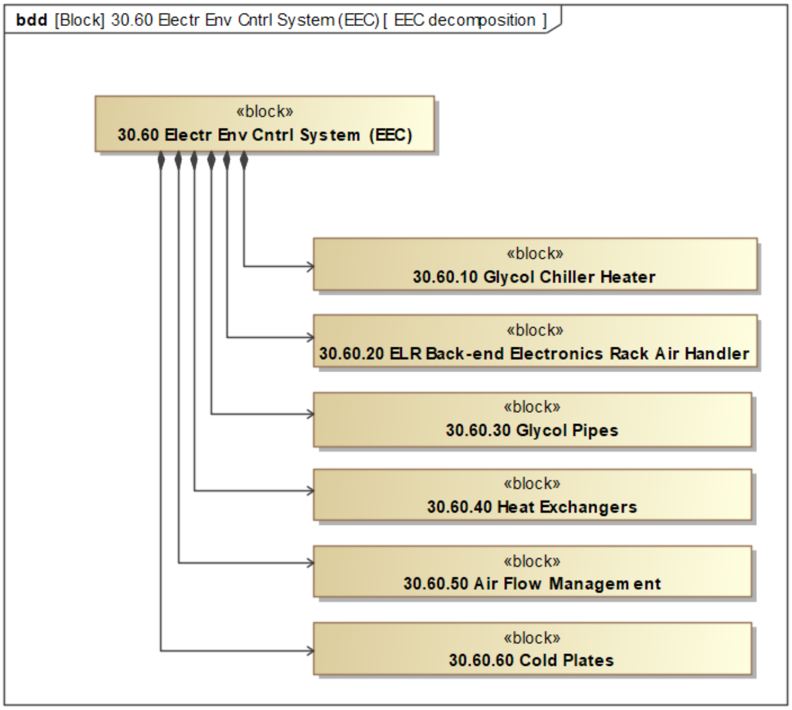

Figure 29: EEC product breakdown structure

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 air conditioner (ANT and SBA).

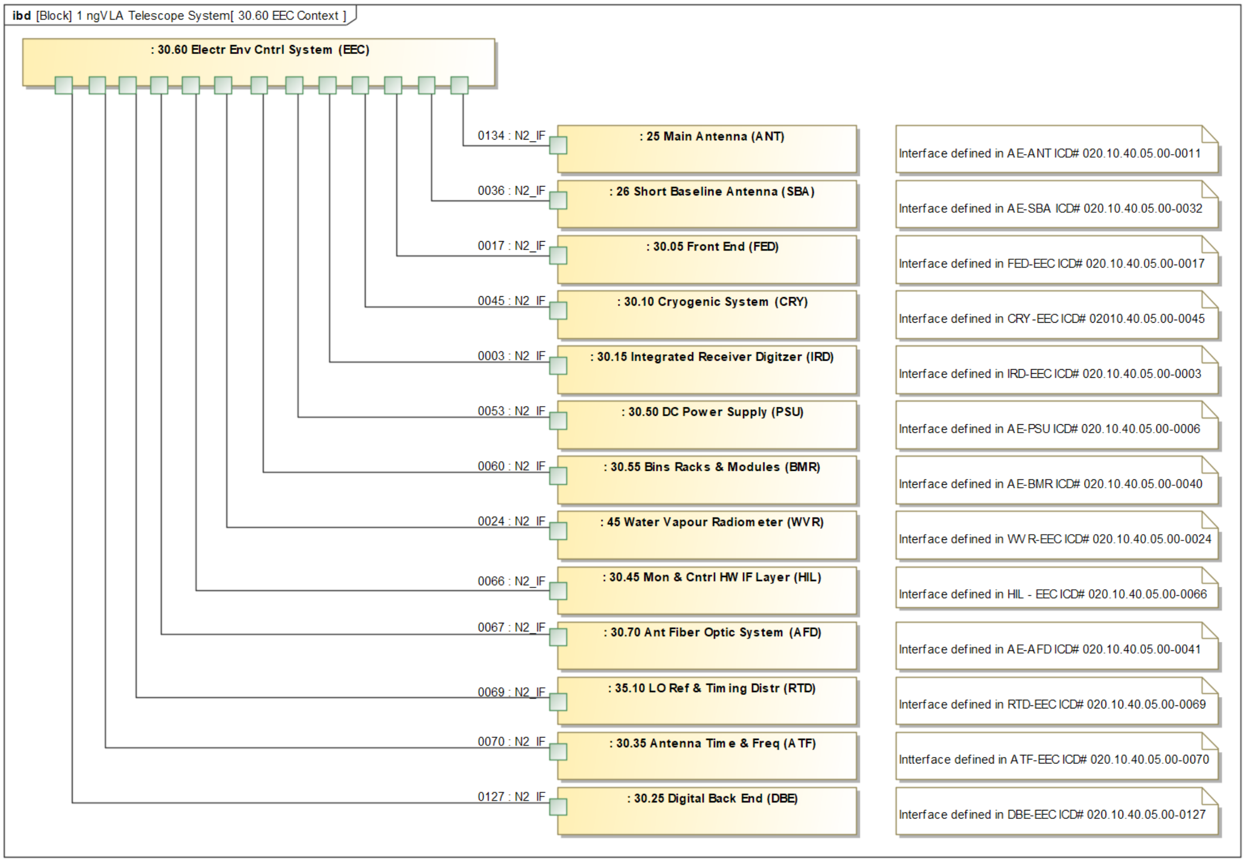

Figure 30: EEC external interfaces

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.

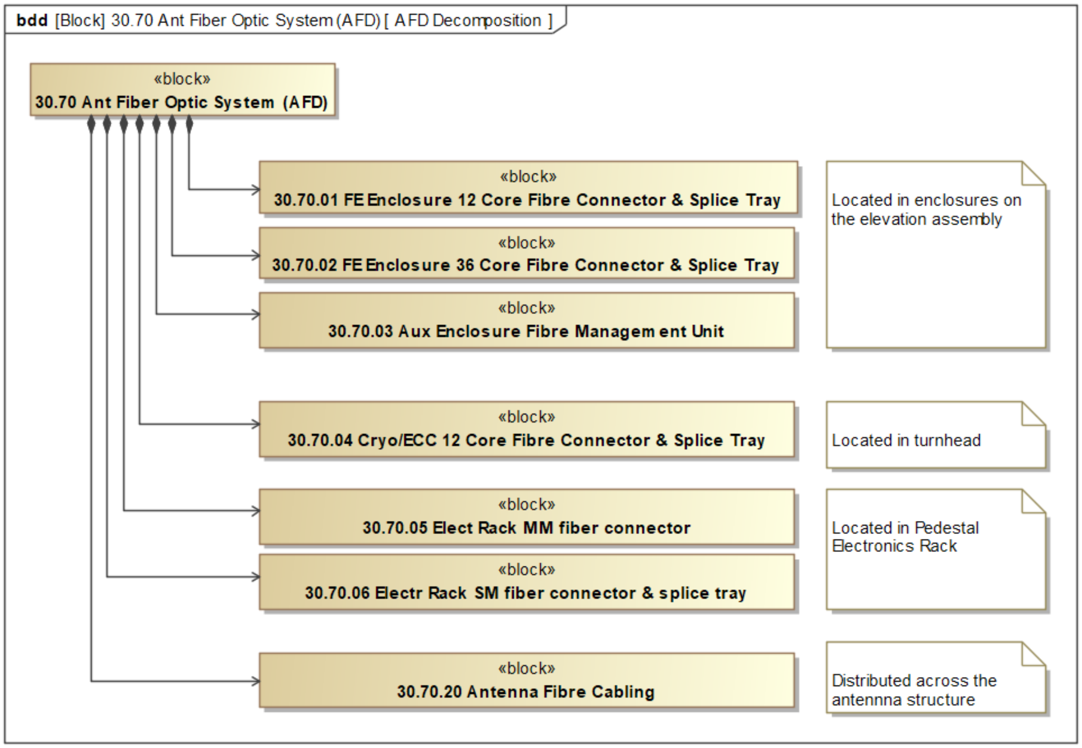

Figure 31: AFD decomposition

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.

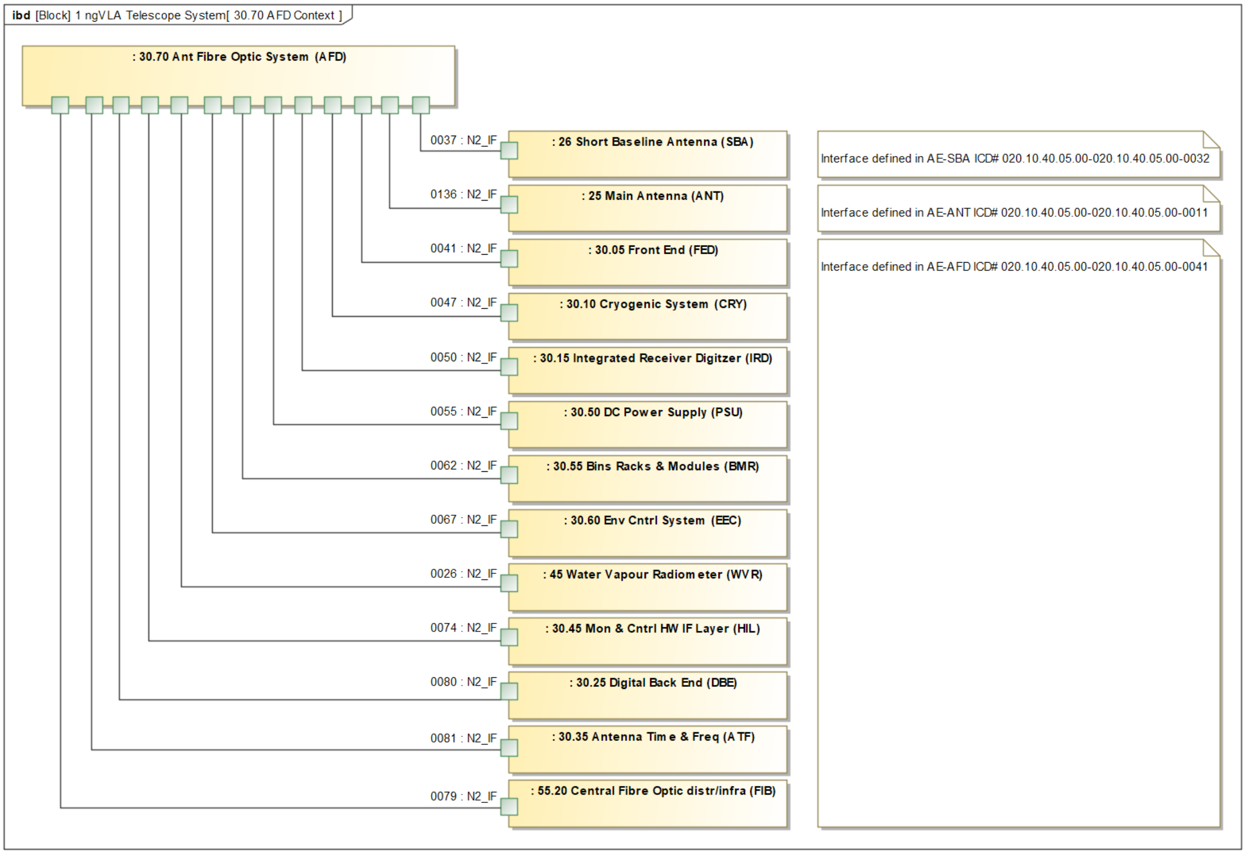

Figure 32: AFD external interfaces

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 sufficiently 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.

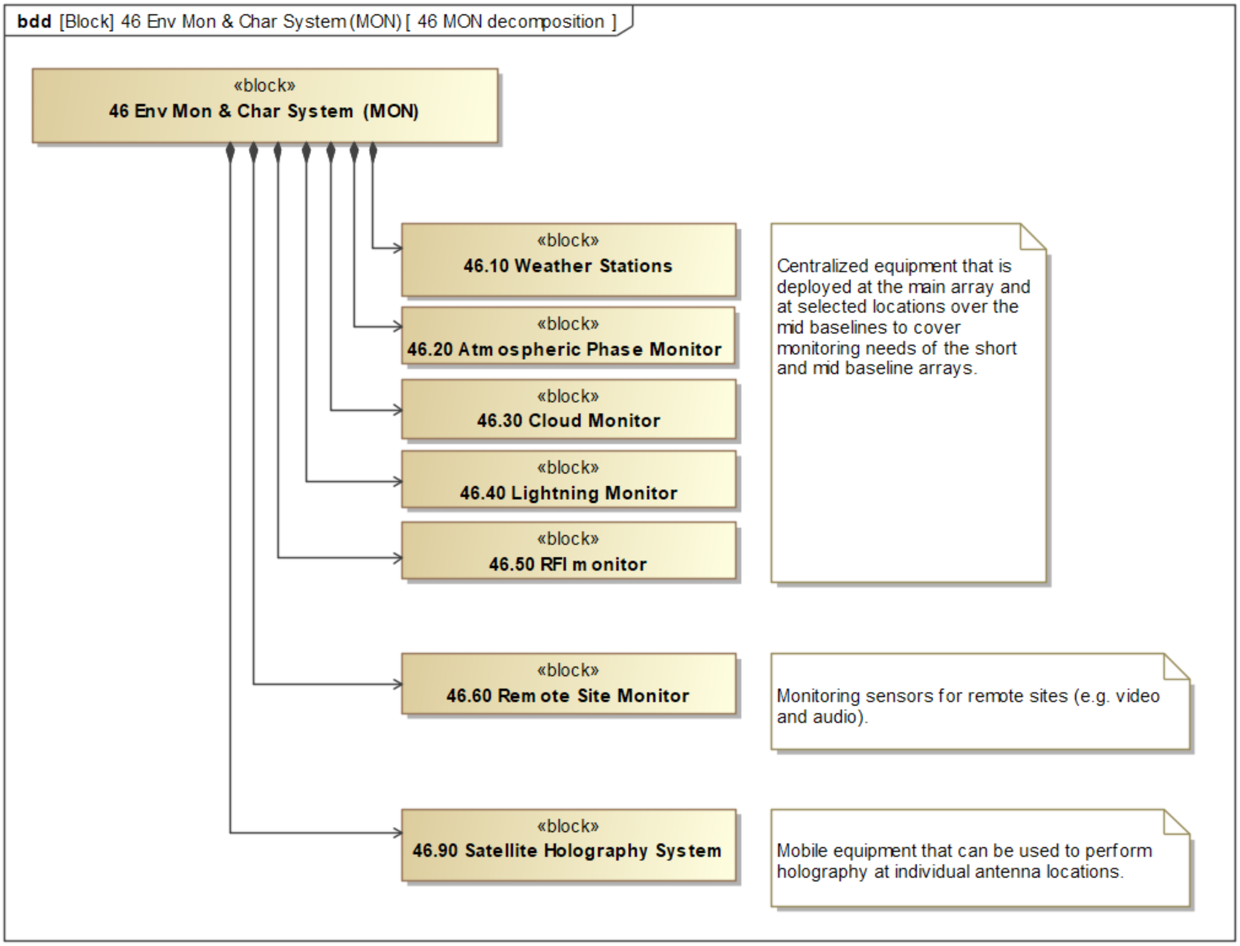

Figure 33: MON decomposition

The MON subsystem has interfaces to the HIL and MCL subsystem for the transfer of the environmental data and for the control of the equipment. It interfaces to 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.

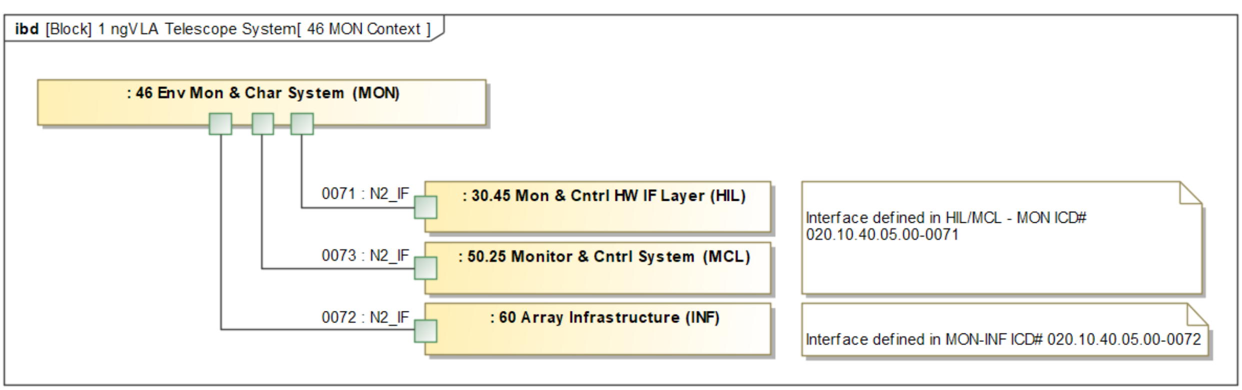

Figure 34: MON external interfaces

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.

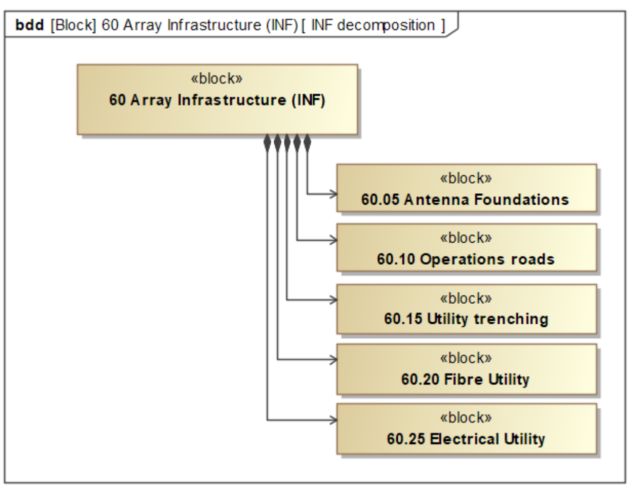

Figure 35. Array Infrastructure Subsystem Decomposition

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

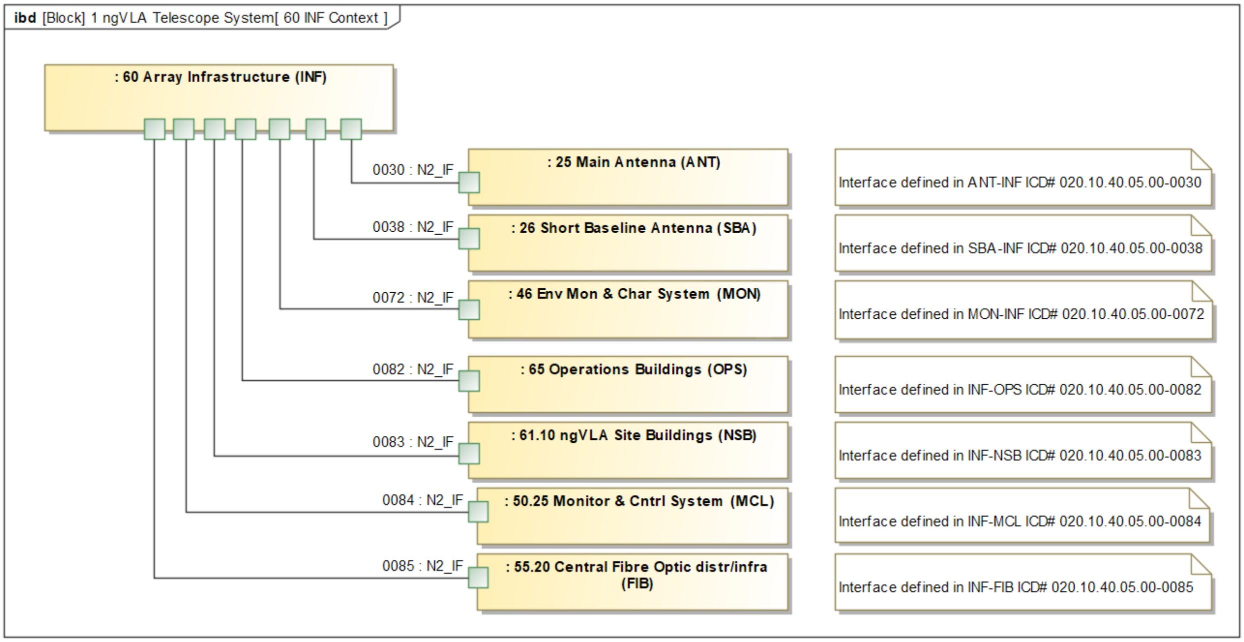

Figure 36. Array Infrastructure Context Diagram

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.

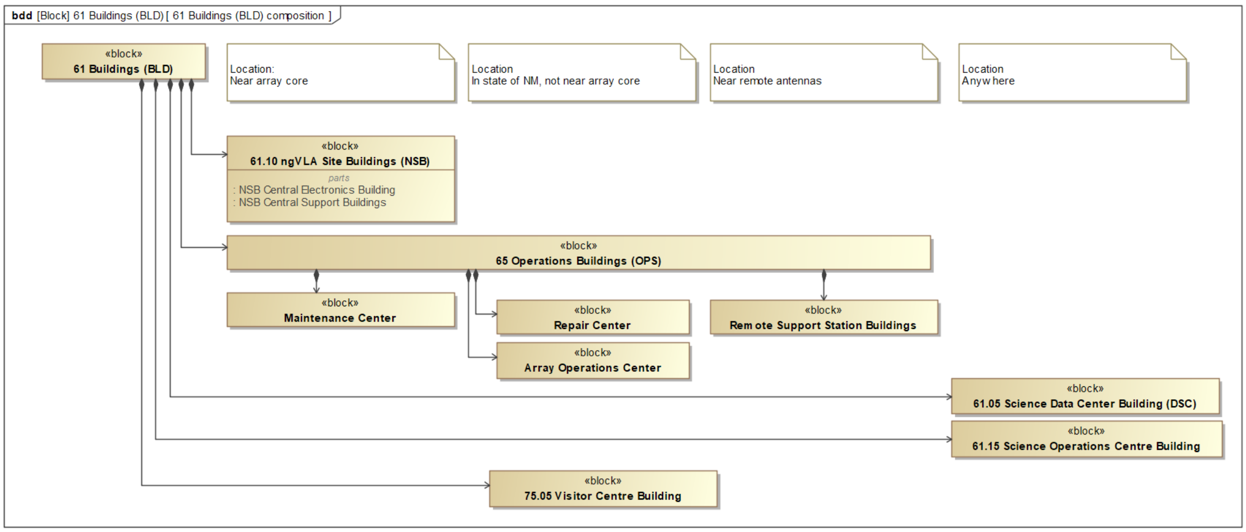

Figure 37: Buildings decomposition and location

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.

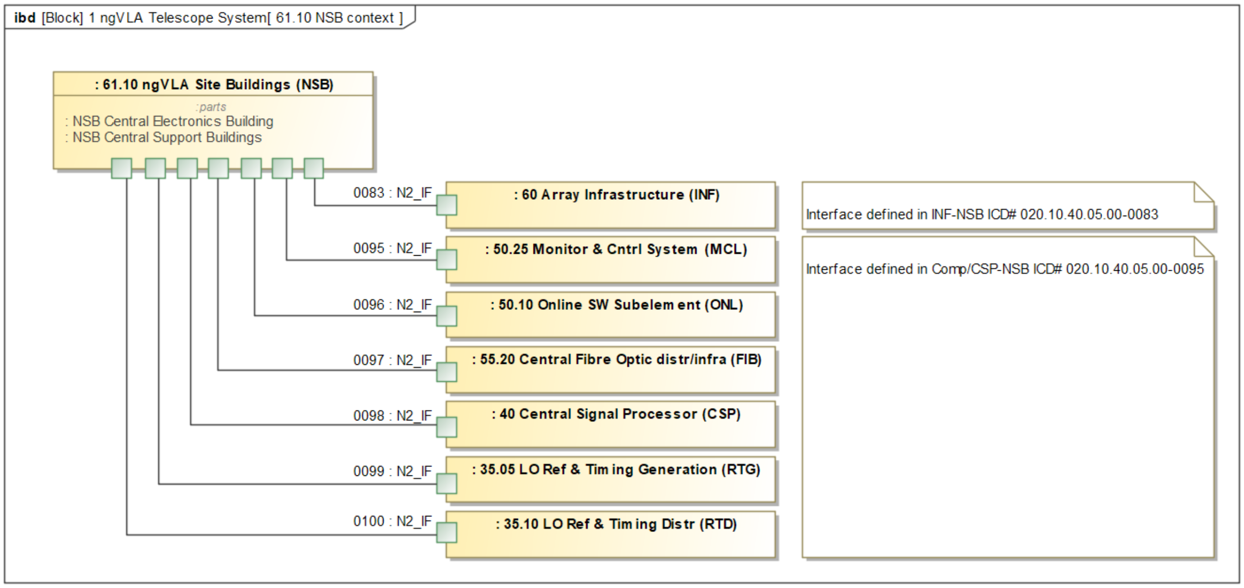

Figure 38. ngVLA Site Buildings Context Diagram

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 an incorporated part of 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.

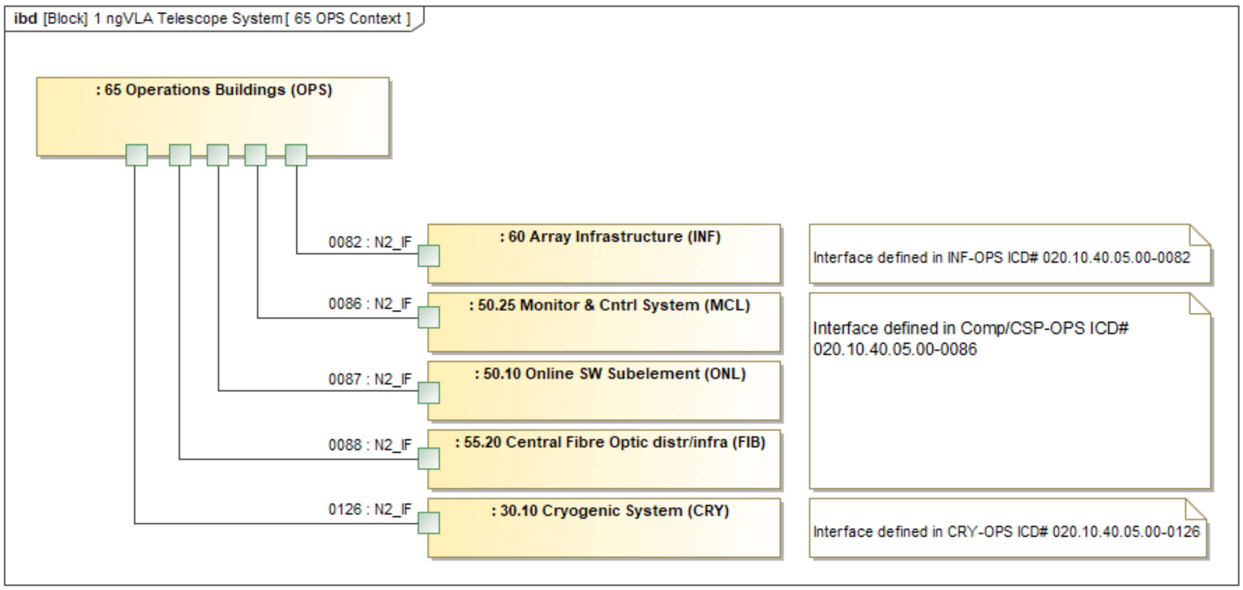

Figure 39. Operations Building Context Diagram

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.

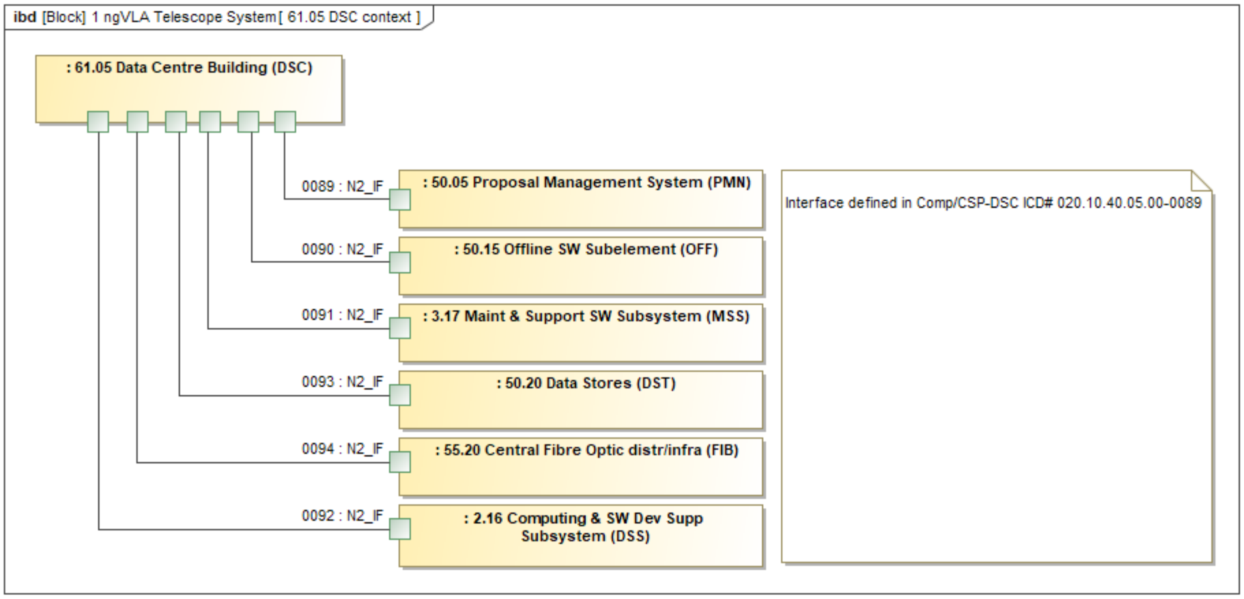

Figure 40. Data Science Center Building Context Diagram

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 Subsystem (CSS)

Figure 41 shows all the subsystems in the scope of the CSS IPT. The reasons behind this subsystem decomposition are:

a) The ngVLA software system will not be implemented from the ground up. Existing and under-development NRAO systems will be adopted or "inherited" by ngVLA. These include the next NRAO Proposal Management System and NRAO Science Archive. Also, ngVLA expects to adopt data processing software infrastructure and solutions as designed by DMS in accordance with the parallelization and performance needs of the ngVLA and ALMA.

b) As specified in requirement STK1100 [AD09] and section 4.7.1 of the System Concept Options & Trade-Offs document [AD10], the system will archive the visibility data generated by the CSP before executing post-processing pipelines to generate high-level data products (e.g., images and cubes).

c) The computing and software systems will be distributed across several of ngVLA sites: control systems will be deployed in the Central Electronics Building, while the Science Archive and post-processing systems will be deployed in the Science Operations and Data Center.

The visibility data archive defines a boundary between the Online SW Sub-element (ONL) and the Offline SW Sub-element. While the design of ONL is driven by need to control the operations of the telescope and perform observations; the OFF design revolves around providing services on top of the science archive data. For ngVLA, these two systems are separated geographically as well.

The PMN subsystem supports NRAO proposal management processes. This system will be based on the Telescope Time Allocation Tools project, which aims to implement a major upgrade to the present NRAO proposal management systems.

Several centralized databases and data storage systems that are used by more than one component or subsystem have been put under the DST subsystem. This organization allows to defer decisions of segregating or integrating them in one or more databases for the design stage of the project.

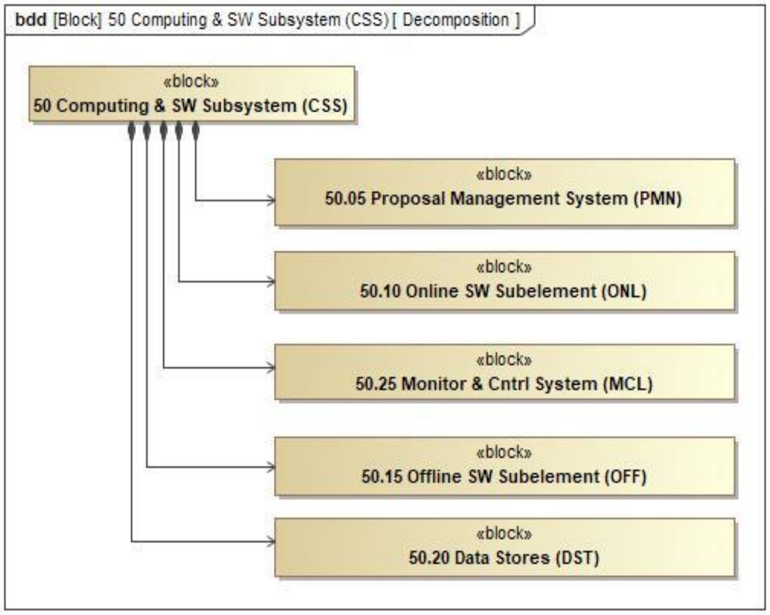

Figure 41: Decomposition diagram for the Computing and SW Subsystem

The subsystems defined in this diagram are:

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

(b) **50.05 Proposal Management System (PMN)**: This subsystem supports the ngVLA telescope time allocation processes, including the solicitation of proposals for each observing cycle, the proposal submissions from PIs, the review process and time allocation, approval and closeout processes. It supports these processes through the Telescope Time Allocation System, a common NRAO system for all its supported telescopes. The ngVLA Proposal Management System extends the TTA system to comply with its specific requirements. The PMN system generates Observing Specifications which are used to create the data structures required to conduct observations (Scheduling Blocks).

(c) **50.10 Online SW Sub-element (ONL)**: The online subsystem selects scheduling blocks and executes them in a sub-array. It coordinates all operations necessary to perform observations, resulting in archived science data. The system reads configurations and calibrations from the telescope configuration database and applies them in the corresponding telescope systems. It continuously monitors the state of the telescope, saving the monitoring data and alarms in the Engineering database. This database also includes integrated logs generated by all software components as they perform their operations.

(d) **50.15 Offline SW Sub-element (OFF)**: This subsystem is responsible for all post-observation operations performed on the collected science data, including the generation of derived data products, support for quality assurance activities, and the provision of interfaces to search for and retrieve data products.

(e) **50.20 Data Stores (DST)**: The data stores included in this package are logical and are deployed into physical storage systems and databases depending on their requirements. They may be consolidated or segregated as necessary.

(f) **50.25 Monitor and Control System (MCL)**: This system is composed by software components necessary to connect the high-level software with the telescope hardware. It provides a level of isolation between a high-level model of the array and the low-level details involved in accessing its hardware, using protocols such as OPC UA.

Figure 42 shows the main system data flows. The PMN system handles the proposal management processes through several services. Proposals are eventually transformed into a set of scheduling blocks, which are read and executed by the ONL subsystem. The ONL subsystem commands the telescope hardware by means of the MCL subsystem. The scheduling blocks execution results in sub-band data being sent from the CSP to the ONL subsystem, which then processes it and sends the science data for ingestion into the OFF subsystem. The MCL subsystem captures engineering data which is sent to the Engineering Database and the MSS subsystem. Once the science data is received by the OFF subsystem, it is processed to generate SRDP products.

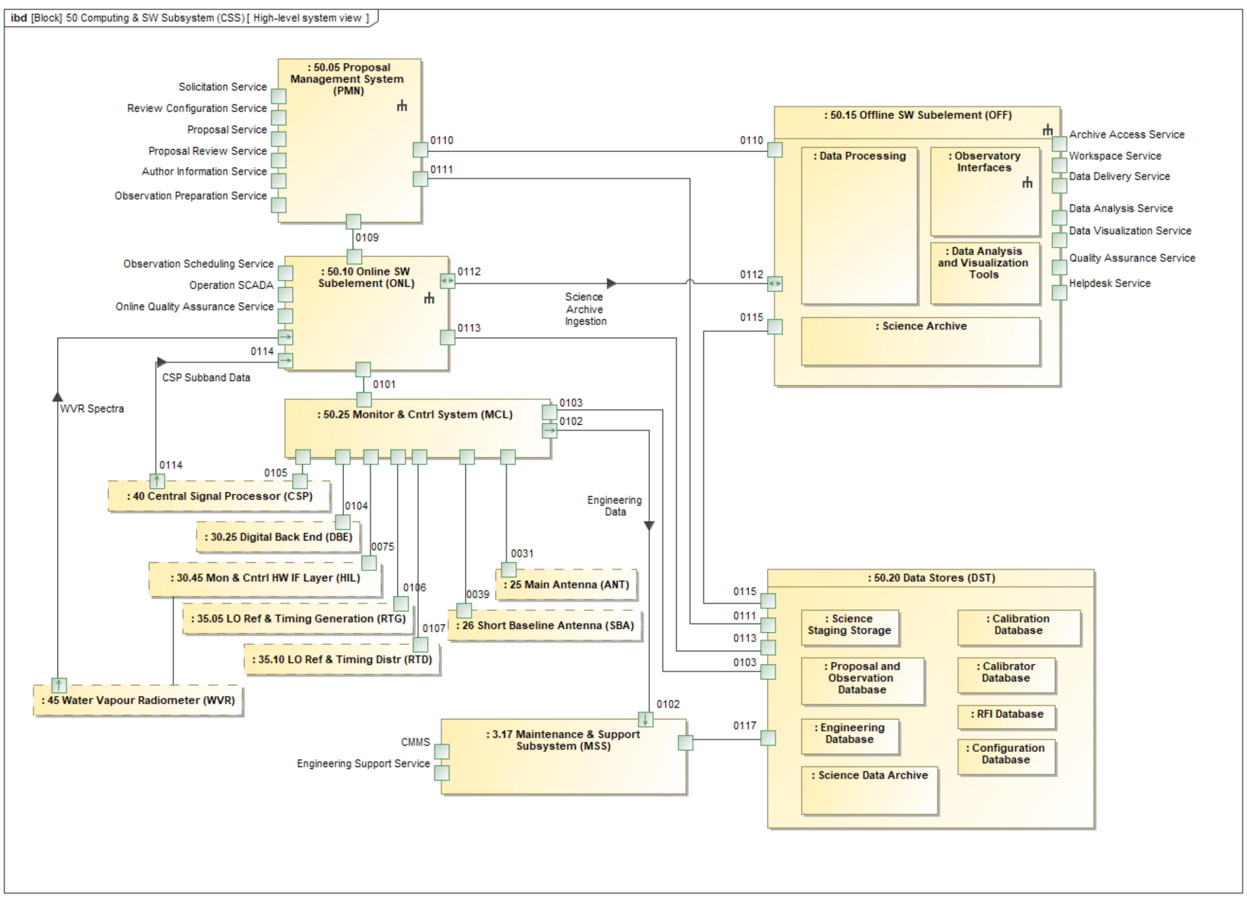

Figure 42: Internal block diagram of the Computing & Software System.

This diagram shows a high-level view of the entire system. External user interfaces are shown as unconnected ports (e.g. Solicitation Service, Review Configuration Service, etc.), and connected ports represent the internal interfaces. The diagram also shows the main data streams (CSP Sub-band Data from the CSP, Science Data for archival ingestion, and Engineering Data). This diagram also shows the (external) H/W components that the system interacts with, through the Monitor and Control System.

Figure 42 also shows the main user interfaces to the system. These are:

(a) **Solicitation Service**: The Solicitation Service supports configuring and opening a solicitation, modifying capabilities, and testing proposal validation.

(b) **Review Configuration Service**: The Review Configuration Service supports managing review groups, assigning reviewers to groups, and assigning proposals to reviewers.

(c) **Proposal Service**: The Proposal Service supports creating and vetting proposals.

(d) **Proposal Review Service**: The Proposal Review Service supports Panel Proposal and Observatory Site review processes.

(e) **Author Information Service**: The Author Information Service supports accessing author information via the NRAO Account System or configuration files. NRAO is in the planning phase of a project to update its user account system and this part of the design will be revisited at a later date.

(f) **Observation Preparation Service**: Interface that allows the user to generate Scheduling Blocks from the Observing Specifications created by the TTA tools or from scratch, and to edit and validate the Scheduling Blocks afterwards.

(g) **Observation Scheduling Service**: This is interface provides functionality to create, destroy and query sub-arrays and interact with the scheduling algorithms. This interface aggregates information about the status of the antennas, allowing the Operator to visualize the sets of antennas that can be used in specific sub-arrays. It enables the start and stop of Scheduling Block (SB) execution, and to query the state of executing SBs.

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

(i) **Online Quality Assurance Service**: A Graphical User Interface (GUI) to present online QA data. This data typically includes the phase RMS, pointing and focus offsets, WVR data, etc.

(j) **CMMS**: This interface allows Operations staff to access the Computerized Maintenance Management System. This system provides several functions aimed to effectively organize maintenance operations.

(k) **Engineering Support Service**: This interface allows Engineering support staff to access data from the Engineering Database and provides integrated services to support maintenance operations.

(l) **Archive Access Service**: This Web application allows users to browse and search the Archive contents and retrieve data. It will be based on the present Archive Access Tool (https://data.nrao.edu), adapted for ngVLA.

(m) **Workspace Service**: This Web application lets users access their workspace, where they save references to data products and queries, submit post-processing requests, and manage their execution.

(n) **Data Delivery Service**: Interface to allow users to download datasets from NRAO Science Archive.

(o) **Data Analysis Service**: Interfaces to perform local and remote data analysis operations. These can be browser-based (e.g., Jupyter notebook) and/or based on locally deployable tools.

(p) **Data Visualization Service**: Local and remote interfaces to visualize data and images (probably based on the CARTA system).

(q) **Quality Assurance Service**: This Web application allows QA personnel to access job execution information, Weblogs, etc. The application permits introducing comments and performing actions to follow up QA decisions (accept data products, reject data products, submit for re-processing, submit Helpdesk issues, etc.).

(r) **Helpdesk Service**: This interface provides access to NRAO Helpdesk, which allows users to submit and follow up problems related with observations and post-processing jobs.

4.6.16 Proposal Management Subsystem (PMN)

The systems that compose the Proposal Management System are shown in Figure 43.

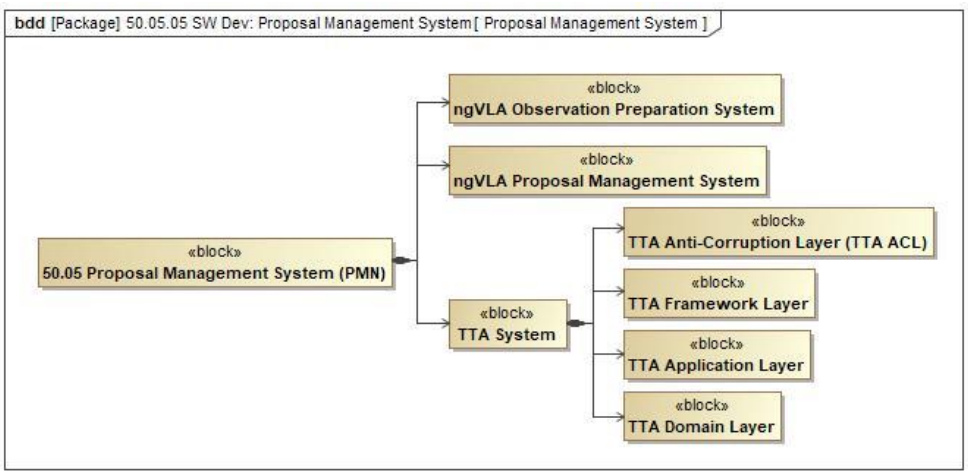

Figure 43: Module decomposition for the PMN system

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

The PMN components are:

(a) **Telescope Time Allocation System**: 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.

(b) **ngVLA Proposal Management System**: This system supports the ngVLA time allocation process, extending the TTA system to comply with ngVLA specific requirements.

(c) **ngVLA Observation Preparation System**: This system transforms observation specifications 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.

Figure 44 shows the external interfaces of the PMS:

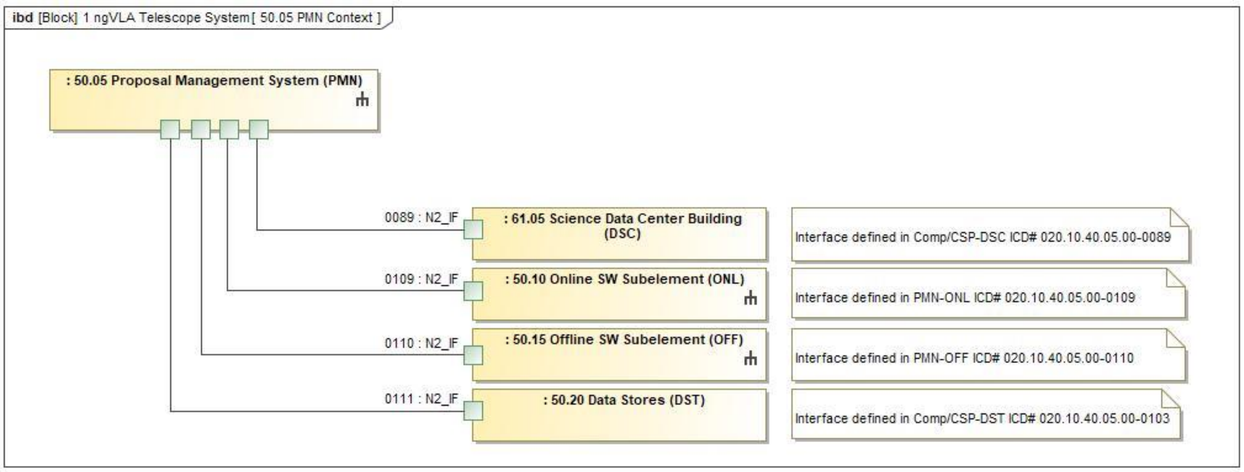

Figure 44: Context diagram for the Proposal Management System

These interfaces are:

(a) 0089 - Interface with the Science Data Center Building (DSC): This interface defines requirements for the computing equipment that will be housed in the DSC, specifying rack space, cooling, and power requirements.

(b) 0109 - Interface with the Online SW Sub-element (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 (i.e. the interface with DST). The ONL subsystem reads these scheduling blocks and executes observations. If other interface is needed between these subsystems, it should be specified in this ICD.

(c) 0110 - Interface with the Offline SW Sub-element (OFF): The interface between the OFF subsystem and PMN is mainly through the data structures stored in the Proposal Management Database (DST). If other interfaces are necessary between PMN and OFF, they should be specified in this ICD.

(d) 0111 - Interface with Data Stores (DST): These are data access interfaces (e.g. SQL or REST interfaces) to the databases in DST.

Figure 45 shows how the sub-elements contained within this subsystem are connected through interfaces. The TTA System is a common NRAO system to handle the proposal management processes for all NRAO observatories. It is designed to be extended through an Anti-corruption Layer by each observatory. The translation of Observation Specifications to Scheduling Blocks is handled by the ngVLA Observation Preparation system component.

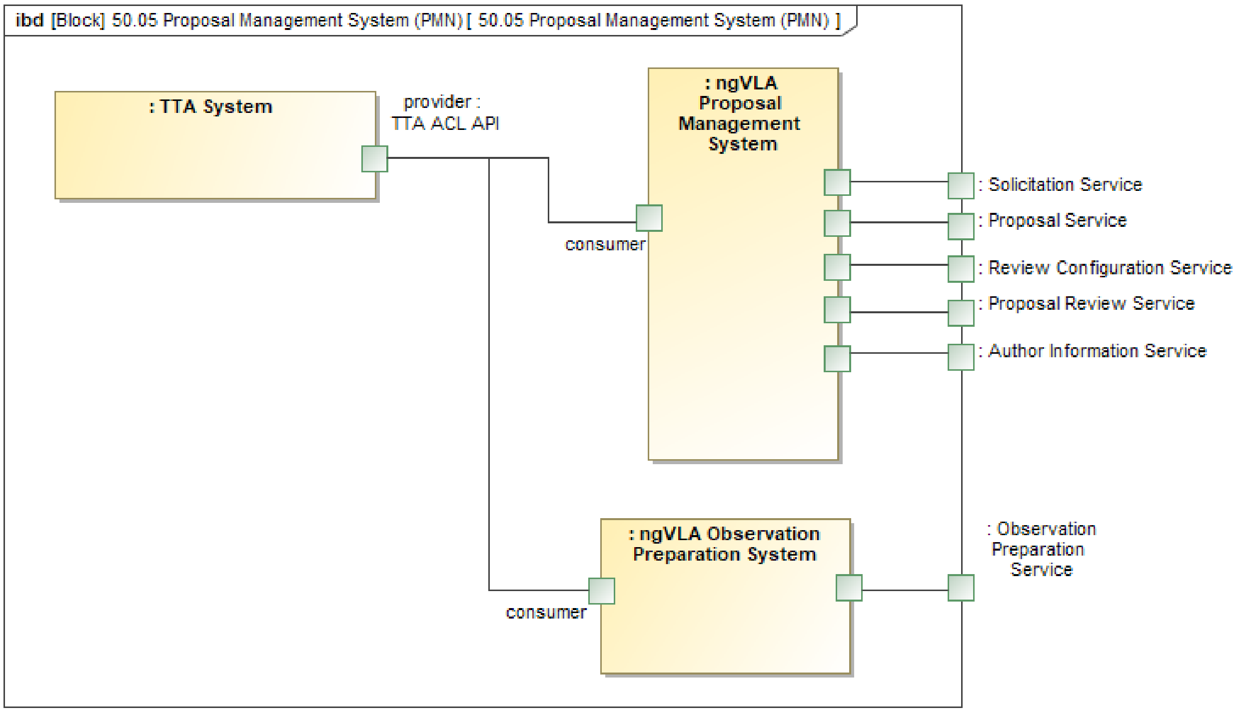

Figure 45: Internal block diagram for the PMN subsystem.

Note on Figure 45: The TTA System implements the core functionality for the telescope time allocation processes for all NRAO observatories. It is designed to be extended for each observatory through extension points defined in the TTA Anti-corruption Layer (TTA ACL API). The ngVLA Proposal Management System implements these extension points and exposes several user interfaces, which are shown as ports in the boundary of the diagram. A separate ngVLA Observation Preparation System implements the required extension points to perform the conversion of the Observation Specification data structures – created by the TTA System – into Scheduling Block structures, which can be edited and validated through the Observation Preparation Service user interface.

4.6.17 Monitor and Control System (MCL)

The Monitor and Control System is a sub-element of the Computing & Software System (CSS). It consists of a set of libraries used by the Online Subsystem to communicate with the telescope hardware elements. It provides a model of the hardware elements which is independent of low-level details involved on the implementation, such as the protocols used to communicate with the hardware elements and mechanisms and patterns used in these interactions (synchronous or asynchronous communications, publish/subscribe, etc.)

These libraries translate the operations defined in this implementation-agnostic model of the telescope into OPC UA commands, providing a layer of isolation between the selected hardware communication protocol and the rest of the system. This layer of isolation is necessary to prevent the rest of the system from being "contaminated" with unnecessary details that would make the migration to a different protocol more difficult in the future, and generally decrease the software maintainability.

The MCL system also provides a simulation version of the high-level telescope model, allowing the rest of the system to be developed as soon as the interfaces are defined and facilitating the integration and testing of the system.

Figure 46 shows how the MCL system is decomposed in SW modules.

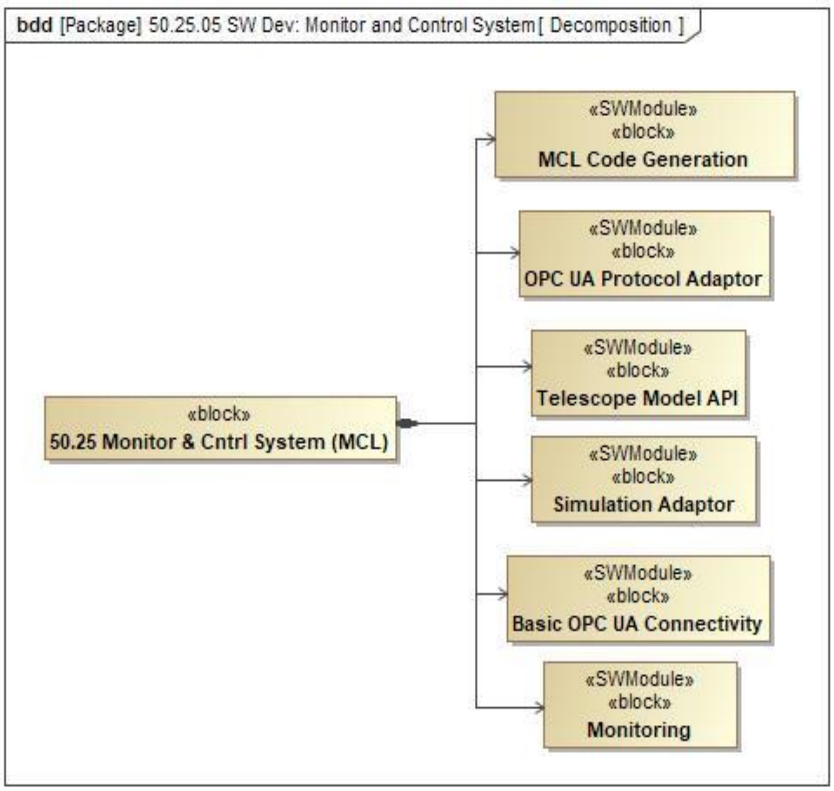

Figure 46: Decomposition of the MCL system in software modules.

These modules are:

(a) **Basic OPC UA Connectivity**: Using the MCL Code Generation framework, this module provides basic connectivity OPC UA servers to be used by HIL to implement the servers. A prototype of this module has already been implemented.

(b) **MCL Code Generation**: This is a code generation framework for OPC UA. These interfaces will be defined in SysML and Model-to-Model and Model-to-Text technologies will be used to transform the SysML model into code. A prototype for this Model Driven Architecture (MDA) transformation has been already implemented.

(c) **Monitoring**: This module provides several components to be used in collecting, streaming and archiving monitoring data.

(d) **OPC UA Protocol Adaptor**: An adaptor for the Telescope Model API, implementing operations in the OPC UA protocol. In practice a plugin architecture or dependency injection techniques can be used implemented to add protocol support.

(e) **Simulation Adaptor**: A simulator for the telescope hardware, to be used for unit and partial integration testing. This module plays the same role as the OPC UA Protocol Adaptor, but in this case, it simulates the system instead of sending OPC UA commands.

(f) **Telescope Model API**: A set of classes implementing a high-level API of the telescope hardware.

Figure 47 below shows the interfaces between MCL and other system elements. MCL has interfaces with all hardware elements. Note that all the interfaces with the elements in the antenna electronics go through the HIL Layer.

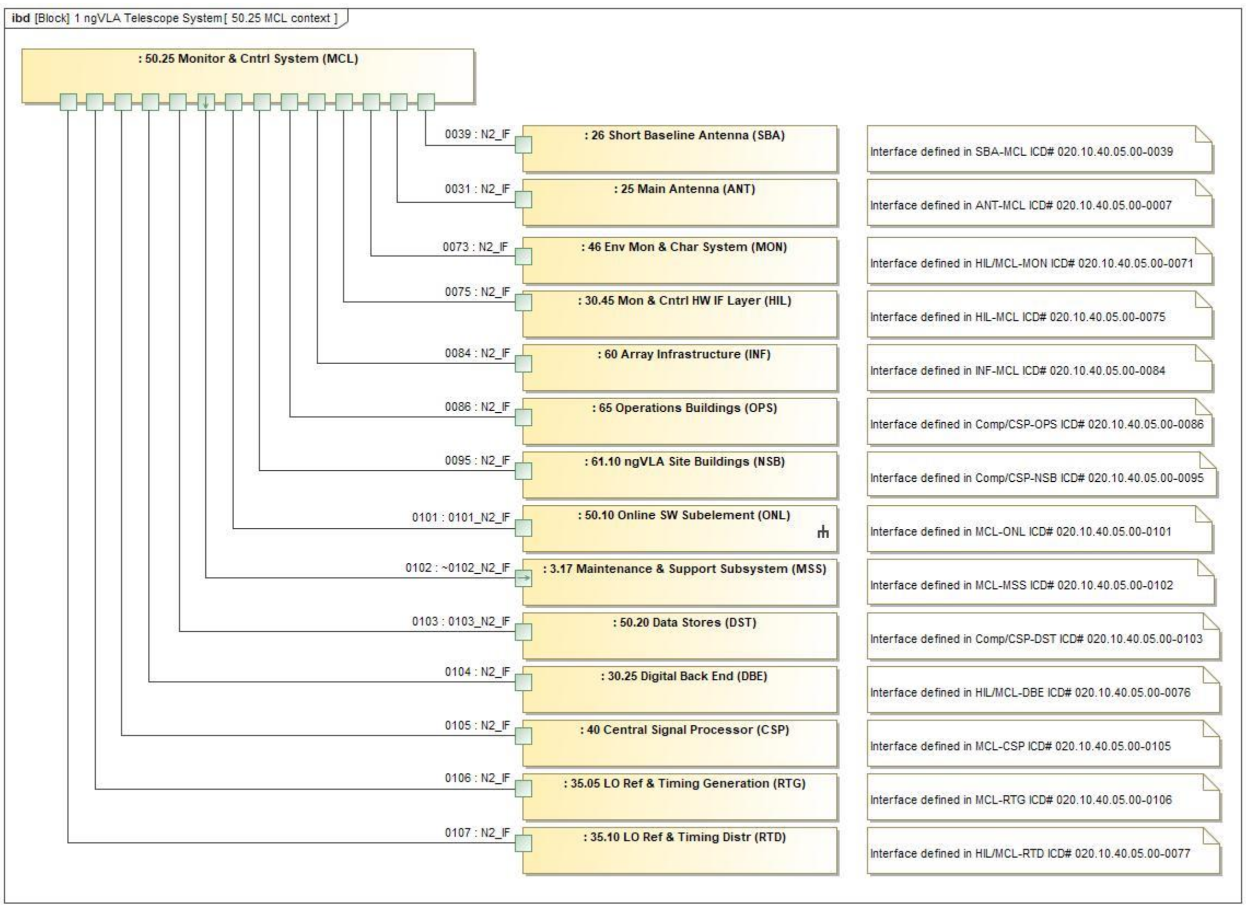

Figure 47: Context diagram for the MCL system

The MCL interfaces are the following:

(a) 0031, 0039 - The interface with the antennas (ANT, SBA) are OPC UA interfaces with the Antenna Control Units (PLCs).

(b) 0075 - The interface with HIL are OPC UA interfaces to the HIL modules. MCL communicates with all the rest of the antenna electronics modules through this interface (FED, CRY, IRD, PSU, EEC, WVR, MON, DBE).

(c) 0105, 0106, 0107 - Interfaces with central electronics (CSP, RTG, RTD) are still TBD. They could be OPC UA interfaces, but other alternatives are also possible. For example, if the CSP is provided by NRC it will most likely offer an interface based on TANGO Controls. As mentioned before, MCL provides a layer of isolation between the H/W protocols and the rest of the system, so multiple protocols can be supported if absolutely necessary.

(d) 0103 - Interface with the Data Stores. The MCL needs to access several databases. It retrieves configuration information from the Telescope Configuration Database, and stores monitoring data into the Engineering Database and Staging file-system, when online processes need to analyze monitoring data stream in real time.

(e) 0101 - The interface with the ONL sub-element is the Application Program Interface (API) to the MCL library.

(f) 0102 - The interface with the MSS sub-system deals with sending Engineering Data, triggering high frequency data acquisition (the oscilloscope function), console, scripting or Labview interfaces for troubleshooting, and other functions still to be defined.

(g) 0195, 0086, 0073 - Other interfaces (NSB, OPS, MON) are still TBD.

4.6.18 Online Software Sub-element (ONL)

The software modules that compose the Online SW Sub-element are shown in Figure 48.

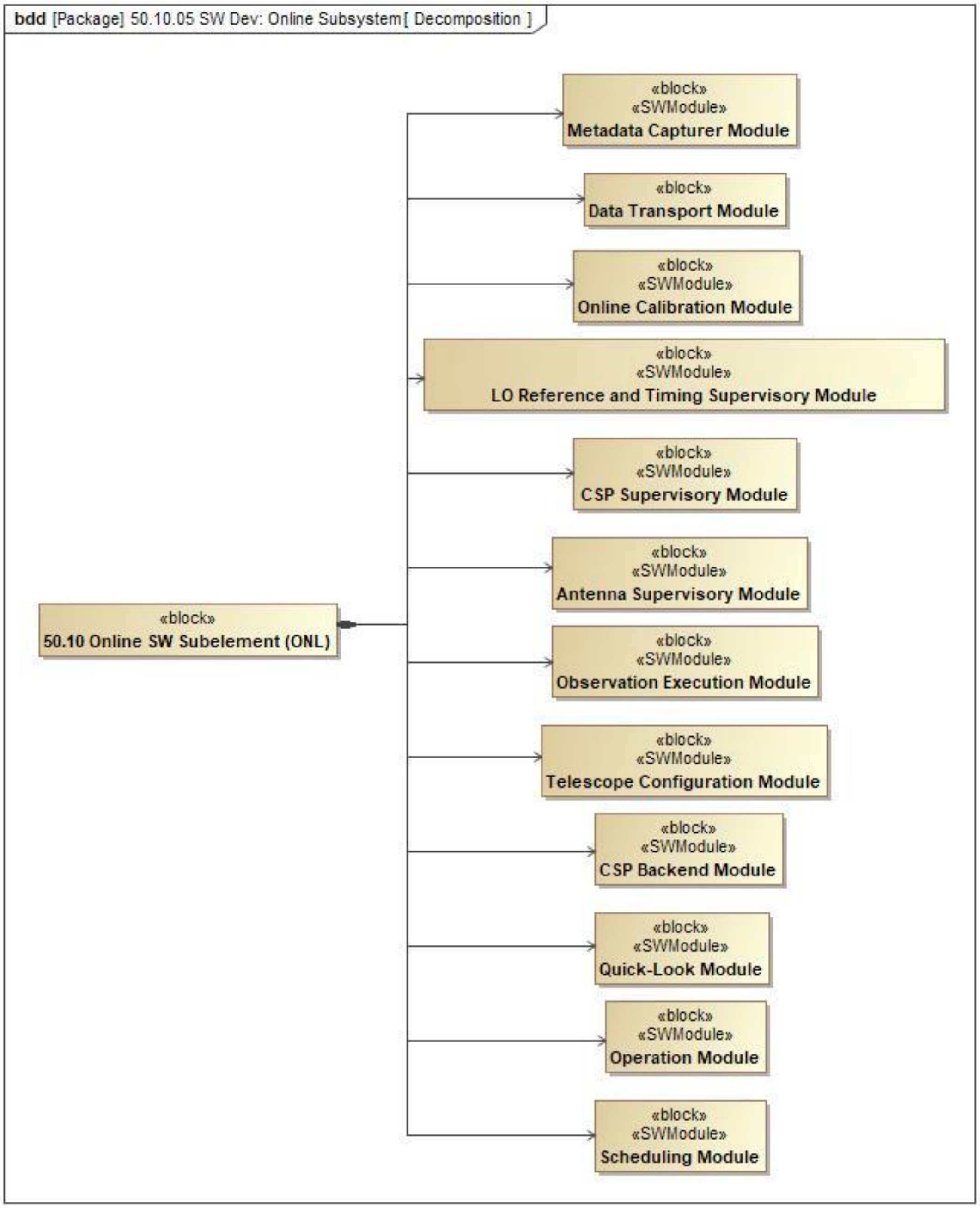

Figure 48: Decomposition of the Online SW Sub-element in SW modules.

These software modules are:

(a) **Metadata Capturer Module**: This module receives data from multiple sources and integrates it all in a series of tables that are saved along with the visibility data.

(b) **Data Transport Module**: The Data Transport Module reads the data/metadata in the Science Staging Storage and sends it to the Science Data Center for post-processing. After the data has been successfully sent to the Science Data Center, it is deleted from the staging storage in order to prevent that it runs out of space.

(c) **Online Calibration Module (TelCal)**: This module reads the visibility data saved during calibration scans and computes several calibration tables. These are saved along with other observation metadata tables, and in some cases are applied on the telescope instrumentation.

(d) **LO Reference and Timing Supervisory Module**: This module consists in software components that control the LO Reference and Timing Generation (RTG) and the LO Reference & Timing Distribution Module (RTD) hardware elements.

(e) **CSP Supervisory Module**: The CSP supervisory module coordinates high level observations commands with the CSP hardware and the CSP backend (CBE), such that CSP resources are allocated according to the requirements of each observation and the CBE is configured to handle the CSP output streams, storing the formatted datasets in the staging storage area. This module also supervises all the CSP parts and monitors their performance.

(f) **Antenna Supervisory Module**: This module uses software components to control antenna hardware elements.

(g) **Observation Execution Module**: The Observation module exposes interfaces to create and destroy sub-arrays, and execute observations on them. This module implements the supported observing modes, which represent different ways to use telescope hardware to perform observations. The execution of an observation results in several commands sent to the telescope hardware, which trigger parallel and sequential operations that are coordinated by the Observation module. This module sends metadata to the Metadata Capture component as the observation proceeds.

(h) **Telescope Configuration Module**: This module provides interfaces for other components to query telescope configuration and calibration data.

(i) **CSP Backend Module**: The Central Signal Processor Backend includes software components to receive CSP data products in real-time and process/format those results into products sent to the staging storage area. All data from the CSP is received by the CBE through the CSP Switched Fabric (CSF) element (basically a large cluster of network switches). The CBE aggregates sub-band data as spectral windows (operation known as stitching), and it averages interferometric data in time and spectral frequency as necessary, given the scheduling block configuration for each scan. It performs these operations for each one of the concurrent sub-array streams produced concurrently by the CSF.

(j) **Quick-Look Module**: This module computes observation quality assurance information and provides interfaces to present this data to the Astronomer on Duty and the Operators.

(k) **Operation Module**: This module provides user interfaces to operate the telescope (operator consoles, etc.)

(l) **Scheduling Module**: This module reads the set of scheduling blocks to be observed from the Proposal and Observation Database and constructs an observation schedule based on current weather conditions and short time prediction, known RFI interferers, target positions, observing frequencies, hardware availability and project data like the completeness status, rank, cadence and stringency [RD16]. The observation schedule defines a program of sub-arrays and their corresponding queues of scheduling blocks.

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

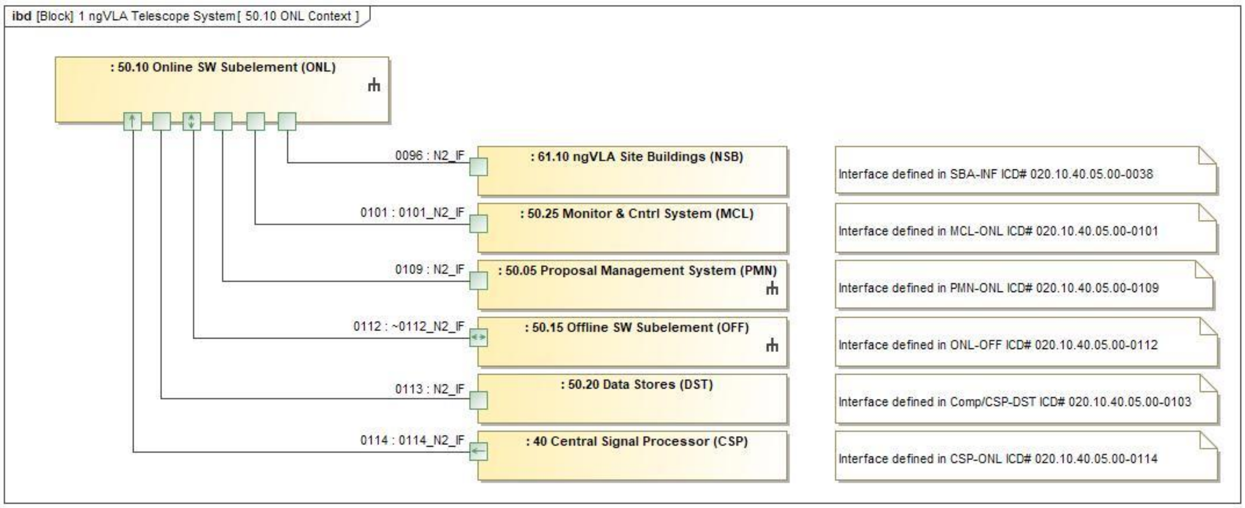

Figure 49: Context diagram for the ONL sub-element

These interfaces are:

(a) 0096 - Interfaces between ONL and ngVLA Site Buildings (NSB), specifying rack space, power and cooling requirements, and networking for the computing servers that will be installed in the NSB.

(b) 0101 - The interface with MCL is an Application Program Interface (API) to the MCL libraries.

(c) 0109 - Although the main communication path between the ONL subsystem and the PMN subsystem is through the scheduling blocks stored in the Proposal database, other interfaces may be needed, for instance to support Target of Opportunity use cases. These are TBD.

(d) 0112 - The interface with the Offline SW Sub-element (OFF) is a streaming interface to send the data products resulting from the execution of scheduling blocks to the Archive.

(e) 0113 - The interface with Data Stores (DST) consists mostly in database APIs (e.g., networked SQL interfaces).

(f) 0114 - The interface with the Central Signal Processor (CSP) is used by the ONL software components to control the CSP.

The ONL sub-element follows a layered architecture based on the Purdue Enterprise Reference Architecture and ANSI/ISA-95. These reference architectures were developed for integrating enterprise systems (observatory systems, in our case) with industrial control systems. These architectures provide a useful way of organizing the activities and time-frames involved in the telescope operations and enabling interoperability with third party systems. It is possible that several of the components that are necessary to implement the control and monitoring system for ngVLA can be procured externally instead of being developed in-house [RD04]. The ISA-95 layers are:

- **Level 0**: The physical processes involved in an astronomical observation.
- **Level 1**: Intelligent devices for sensing and manipulating. Involves the hardware elements that sense, manipulate and convert the signal path. These are PLCs, MIBs, CSP and other hardware devices. The processes involved in these operations have typical time-frames of less than a second.
- **Level 2**: Control systems for monitoring and supervision. The systems that supervise, monitor and control the physical processes. Includes real-time controls and software, 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 Systems. 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 Systems. Manages the activities of the observatory operation. The Proposal Management System is the primary system in this level, establishing the long-term observatory schedules, time allocation, etc. The time frame is days and months.

The distribution of the ONL modules in these layers is shown in Figure 50. The systems depicted in the Level 1 layer are all external hardware elements (represented as segmented line boxes in a SysML IBD diagram). Several systems are involved in controlling and supervising an observation in Level 2. The Observation Execution Module issues commands to the Supervisory Modules, which in turn use the MCS layer to communicate with the systems in level 1. The CSP produces CSP Sub-band data, which is received formatted by the CSP Backend Module and is written to the filesystem in the Science Staging Storage. The Metadata Capturer Module receives metadata from different sources and also writes it to the Science Staging Storage. The Online Calibration Module processes the data/metadata as it is received and sends calibration data the Supervisory Modules. The Operation Module provides supervisory control interfaces for the operator, interacting mostly with the Supervisory Modules, or directly to the Level 1 devices if necessary. Besides the interface between MCL and DST to send monitoring data to be ingested into the Engineering database, the system also provides a direct path between MCL and the Science Staging Storage for monitoring data that needs to be used for online calibration.

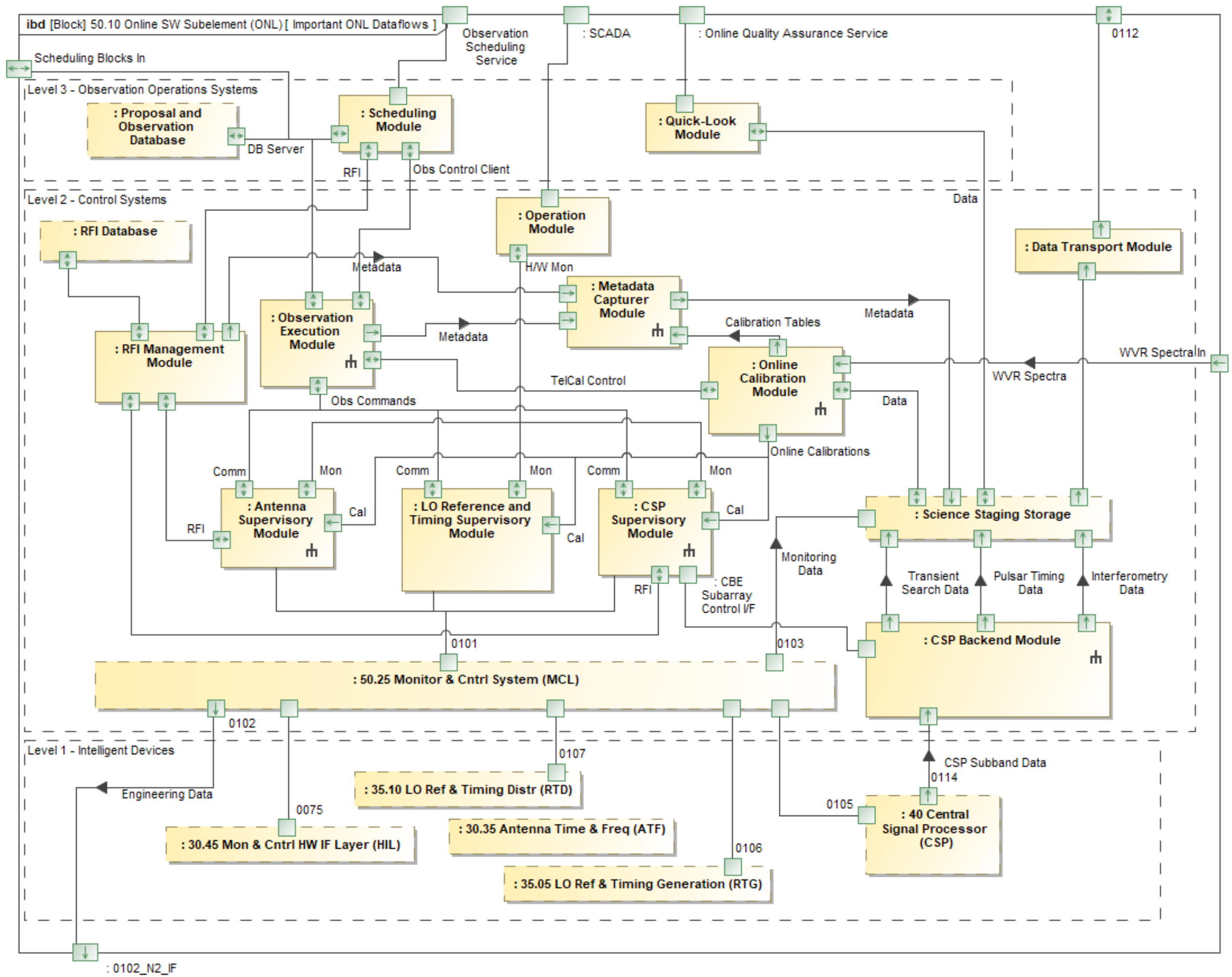

Figure 50: Internal block diagram for the Online subsystem

Figure 50 shows the most important data-flows. Note that this diagram doesn't make assumptions about the nature of the communication between these modules. It can be implemented as asynchronous messaging, synchronous calls or pub/sub messaging. These details will be defined in this subsystem internal ICDs.

The hardware elements belonging to the ONL subsystem are shown in Figure 51.

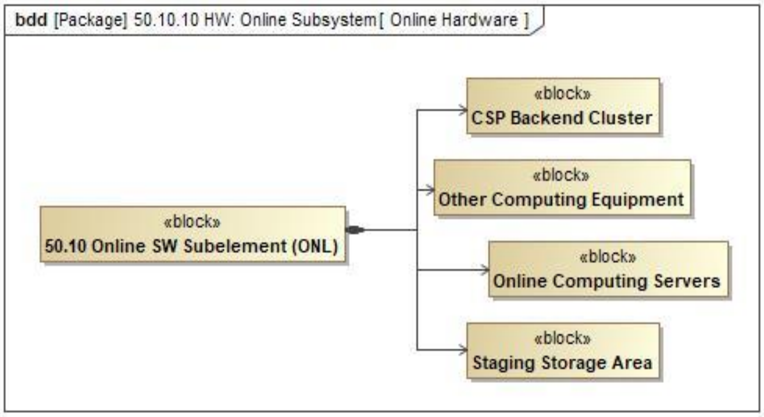

Figure 51: Hardware elements included in the ONL subsystem

These hardware elements are:

(a) **CSP Backend Cluster**: This computing cluster receives the sub-band data stream from the CSP and processes, formats and saves the data on the Staging Storage Area. The Online Calibration software (a.k.a. TelCal) will be deployed here, as well as post-correlation RFI software, implemented as part of the CSP Backend Module software.

(b) **Online Computing Servers**: Computing servers necessary to deploy the Online Subsystem software.

(c) **Other Computing Equipment**: Networking equipment, firewalls, etc.

(d) **Staging Storage Area**: This is a storage system (most probably a high-performance system like Lustre) that receives the formatted area while it is being transferred to the Science and Data Processing Center.

4.6.19 Offline Software Sub-element (OFF)

The system architecture presented in this report reflects a top-down design from the science use cases, science requirements and stakeholder requirements. A related programmatic stakeholder requirement is to share a common platform with the ALMA telescope for the Data Processing module. The interface definition and internal design of this module will require iteration with the associated observatory staff responsible for designing this common platform (ngCASA). The internal architecture of this module, a significant source of total system complexity, is therefore not described here. The architecture of this module will be elaborated and reviewed in a separate sub-system conceptual design review.

The software modules that compose the Offline SW Sub-element are shown in Figure 52.

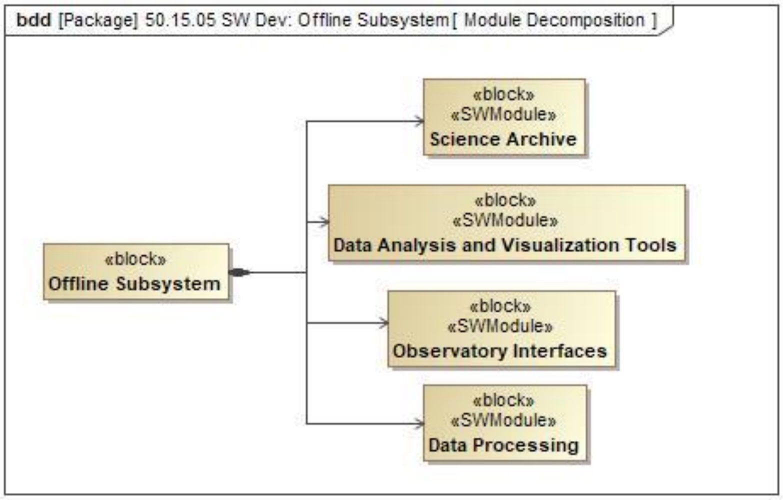

Figure 52: High-level decomposition of the Offline Subsystem in software modules.

The Offline software modules are:

(a) **Science Archive**: The Science Archive is the final repository for all data products. Based in the current NRAO Archive, it consists of a metadata database, a file storage system, and services constructed around them. This system will represent a significant upgrade to the current archive system, in order to comply with ngVLA requirements.

(b) **Data Analysis and Visualization Tools**: These are tools necessary to analyze ngVLA datasets and images, which will likely be provided as remote services, cloud-deployable services and as packages for users to download and install in their local machines. It will probably include services constructed around the CARTA image visualization system.

(c) **Observatory Interfaces**: This module consists of Web applications that provide services constructed around the data stored in the Science Archive. This module includes interfaces to allow PIs to track the status of their observations, access their data, submit re-processing jobs, and support quality assurance operations. It also includes Virtual Observatory compatible interfaces.

(d) **Data Processing**: This module includes pipelines for the generation of science data products and processing infrastructure. The infrastructure will be based on ngCASA. This infrastructure will require significant improvements on parallelization and performance in order to scale to the data rates expected for ngVLA.

Figure 53 shows the interfaces between the OFF sub-element and external system elements.

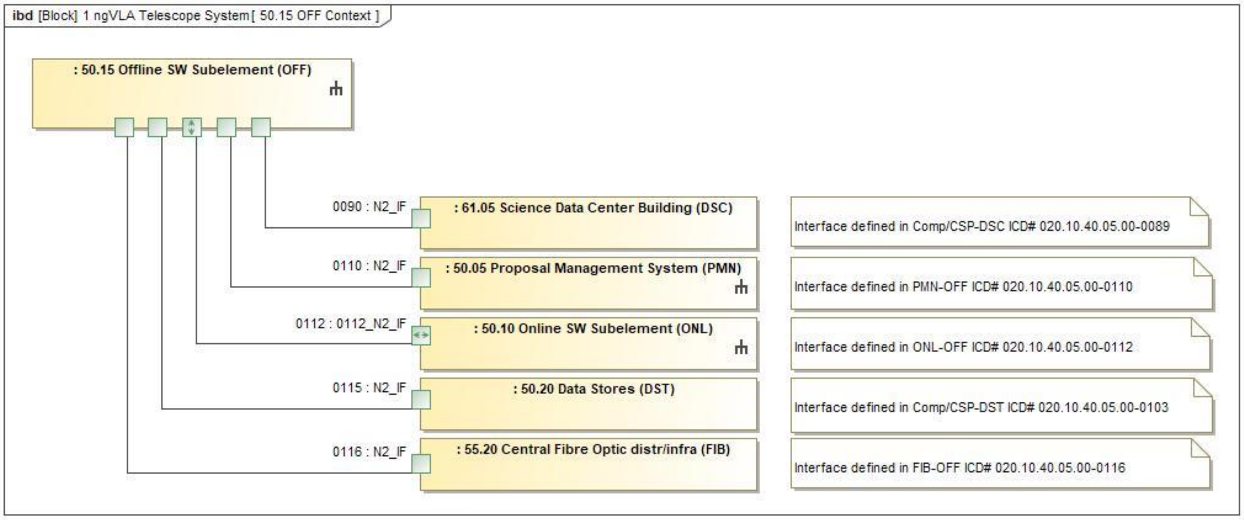

Figure 53: Offline SW Sub-element context diagram.

The Offline SW external interfaces are:

(a) Interface with the Science Data Center Building (DSC). The computing capabilities that the Offline Sub-element needs to provide in order to process the data generated by the telescope put it in the large datacenter or super-computer category. This interface needs to specify power, cooling, rack space and all other requirements necessary to accommodate these computational resources in the DSC.

(b) Interface with the Proposal Management System (PMN). The data processing carried on by the Offline sub-element requires parameters derived from the proposal.

(c) Interface with the Online SW Sub-element (ONL). The Online SW sub-element generates raw data that is transported to the Offline sub-element for archival and post-processing. This interface specifies the details involved in this interaction. Besides this, other interfaces may be necessary, addressing for instance the need for the Scheduling module in the ONL sub-element to query for available computational capacity before scheduling observations.

(d) Interface with Data Stores (DST). The interface with Data Stores (DST) consists mostly in database APIs (e.g., networked SQL interfaces).

(e) Interface with Central Fiber Optic Distribution/Infrastructure (FIB). The FIB subsystem includes the data networks required to distribute the astronomical data from the central processor building to the data center for offline data processing.

The hardware elements belonging to the OFF subsystem are shown in Figure 54.

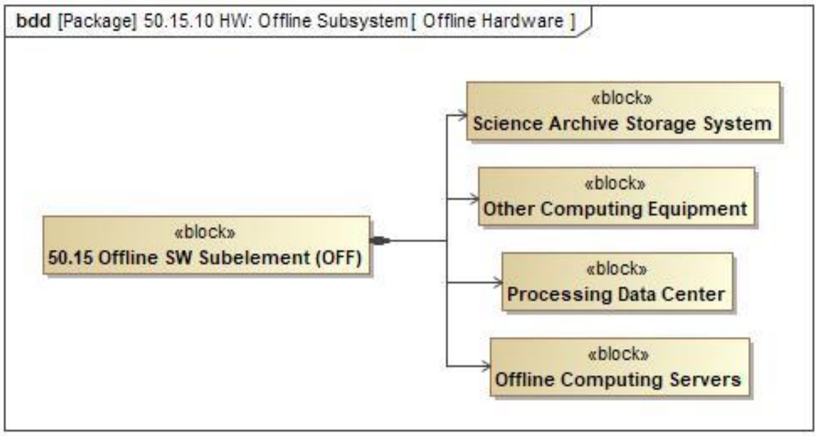

Figure 54: Computing equipment included in the Offline subsystem.

These hardware elements are:

(a) **Offline Computing Servers**: Computing servers necessary to deploy the Offline Subsystem software.

(b) **Other Computing Equipment**: Networking equipment, firewalls, etc.

(c) **Processing Data Center**: This is a peta-scale data center. It is estimated [RD05] that this system should be capable of sustaining a throughput of 60 PFLOPS/second in order to process a set of observations that generates a similar load than the Reference Observing Program.

The model that will be adopted to realize this data center is TBD. In-house, commercial leasing (hosting, colocation or wholesale), cloud computing, a partnership with a national supercomputing facility or international partners that are willing to provide their own data processing facilities are possibilities. A hybrid approach is likely.

The CSS IPT will perform a trade analysis of these different alternatives. It is worth noting that a data center of this size will require megawatt-scale power and impose significant operational costs and it's well beyond the size of current NRAO systems (by a magnitude of 10^3 at least).

(d) **Science Archive Storage System**: The Science Archive storage system. It is estimated [RD05] that the project will generate 20 PB/Month of raw visibility data, for a distribution of science cases similar to the ROP.

The elements included in the Offline sub-system are arguably the most challenging elements required for ngVLA in the Computing and Software IPT. The data rates that the ngVLA array will generate will require a super-computing facility and massive parallelization at a scale not possible yet with current NRAO data processing systems. The development of this part of the architecture is being carried on several on-going projects:

1. An investigation of parallelization alternatives for the data processing system, including the application of hardware acceleration technology (GPU) on calibration and imaging processing, and several potential algorithmic optimizations. A summary of its current status is presented in Section 4.6.19.1.

2. The development of a high-level architecture for the Offline subsystem, researching suitable reference architectures and evaluating their applicability and trade-offs for ngVLA requirements. The NIST Big Data Reference Architecture has been selected preliminarily, a summary of which can be found in section 4.6.19.2.

3. The development of Next Generation CASA (ngCASA) system. ngVLA expects to adopt software infrastructure and solutions as designed by DMS in accordance with the parallelization and performance needs of the ngVLA and ALMA.

4.6.19.1 Data Processing Parallelization

The Data Processing Module is responsible for all the telescope functions that occur after an observation's raw data has been stored in the Science Archive. These functions include the generation of derived data products (image cubes), support for quality assurance activities, and interfaces for searching, visualizing, and retrieving science products. Table 1 shows the telescope's expected rates for interferometric data, estimated from the science cases included in the ROP [RD12]. These figures are large enough to make it unlikely that end users will have in-house computational resources to calibrate and image the raw data locally, so providing these computational resources is central to the ngVLA facility concept. This changes the present interaction model for most users - instead of downloading the visibility data and using a full data reduction software package on local computing resources, high-level data products will be generated by the observatory for all standard observing modes. Services will also be provided for the user to perform quality assurance, submit jobs for custom pipeline re-processing, and carry out analysis and visualization over these high-level data products. All of these services can be developed under the general architecture of the NIST Big Data Reference Architecture, described in the next section.

Science Case	Use Fraction	Vis Per Hour	Data Rate	Storage Rate
KSG1 Driving Cont. Band 6 e.g. Taurus disk	9%	73.19 GVis	0.081 GB/s	0.21 PB/Month
KSG1 Driving Cont. Band 4 e.g. Taurus disk	4%	216.28 GVis	0.240 GB/s	0.63 PB/Month
KSG2 Driving Line Band 5 e.g. Sgr B2(N)	4%	97241.83 GVis	108.046 GB/s	284.14 PB/Month
KSG2 Driving Line Band 4 e.g. Sgr B2(N)	1%	72129.85 GVis	80.144 GB/s	210.76 PB/Month
KSG2 Driving Line Band 3 e.g. Sgr B2(N)	1%	119342.01 GVis	132.602 GB/s	348.72 PB/Month
KSG3 Driving Line Band 5 e.g. COSMOS	4%	5985.35 GVis	6.650 GB/s	17.49 PB/Month
KSG3 Driving Line Band 4 e.g. COSMOS	1%	2996.82 GVis	3.330 GB/s	8.76 PB/Month
KSG3 Driving Line Band 3 e.g. COSMOS	1%	3030.45 GVis	3.367 GB/s	8.85 PB/Month
KSG3 Driving Line Band 6 e.g. Spiderweb galaxy	2%	11.16 GVis	0.012 GB/s	0.03 PB/Month
KSG3 Driving Line Band 5 e.g. Spiderweb galaxy	1%	11.16 GVis	0.012 GB/s	0.03 PB/Month

KSG3 Driving Line Band 4 e.g. Spiderweb galaxy	1%	5.58 GVis	0.006 GB/s	0.02 PB/Month
KSG3 Driving Line Band 6 e.g. Virgo Cluster	7%	3232.05 GVis	3.591 GB/s	9.44 PB/Month
KSG3 Driving Line Band 1 e.g. M81 Group	11%	149.48 GVis	0.166 GB/s	0.44 PB/Month
KSG3 Driving Line Band 1 e.g. M81 Group	13%	4.66 GVis	0.005 GB/s	0.01 PB/Month
KSG5 Driving Cont. Band 1 OTF Find LIGO event	7%	7347.53 GVis	8.164 GB/s	21.47 PB/Month
KSG5 Driving Cont. Band 4 OTF Find LISA event	7%	1090.82 GVis	1.212 GB/s	3.19 PB/Month
KSG5+4 Driving Cont. Band 2 OTF Find BHs + Possible Pulsars	4%	2034.17 GVis	2.260 GB/s	5.94 PB/Month
KSG5 Driving Cont. Band 3 Gw170817@200Mpc	24%	4.18 GVis	0.005 GB/s	0.01 PB/Month
Avg.:		6898.09 GVis	7.665 GB/s	20.16 PB/Month

Table 2 - Expected data rates, from key science use cases. It is assumed that full polarization is required, and visibilities are stored in half precision (2 bytes/number), with no baseline dependent averaging.

As described in [RD05], it is estimated that a system with a computing capacity of 60 PFLOPs/second will be necessary in order to calibrate and image the input visibility data rate of ~2 GVisibilities/second. This estimate assumes that the dominant contributor in the cost of computing is the process of interpolating the visibility data to/from a regular grid prior to performing the FFT (a.k.a. gridding and de-gridding) and the correction of direction-dependent effects by means of the application of convolutional operators (or Convolution Functions, CF) at the same time that the data is gridded. These direction-dependent effects include compensating for the non-coplanarity of the array, and the effect of the primary beam for different frequencies when observing wide fields of view. Other contributors, such as the execution of deconvolution algorithms to account for the imperfect sampling of the (u,v)-space, calibration, and other overheads are introduced as factors in the model. For now, these factors have been estimated conservatively, while prototype software is being developed and test platforms are procured to measure their values and scaling behavior.

To decrease the cost of the computing platform necessary to support the high-level data product delivery paradigm, the data processing architecture will incorporate Graphical Processing Units (GPUs) to perform the gridding and de-gridding operations. A basic early prototype was developed to assess the potential of the technology [RD07], and a more complete version was developed subsequently, integrating the GPU-gridder into CASA in such a way that large-scale parallelization tests are possible [RD08]. These tests subsequently show that a current state-of-the art GPU (NVIDIA Tesla V100) can sustain a processing rate of 4 MVisibilities/second if the overheads of computing and transferring the CFs into the GPU can be made small enough. The data processing architecture will need to optimize the transfer of the CF data into the GPU in order to fully occupy the computational power of the GPU. Several alternatives are also being studied, including moving the computation of the CF into the GPU.

Processing ngVLA observations will require a super-computer with hundreds to thousands of computer nodes equipped with GPUs (500 machines, if the processing rate of 4 MVis/sec can be realized). This level of parallelization will require extensive changes in the CASA code, including optimizing the use of memory, breaking down monolithic tasks into components that can be executed in multiple machines, a new data format designed to optimize I/O operations, and a pipeline system that can manage thousands of parallel jobs, with complex dependency graphs, that can withstand hardware failures in one or more nodes while processing.

Parallelizing at this scale can be challenging due to the effects of serial operations and overheads. One example of this for ngVLA is the process of deconvolution, which is executed after transforming the gridded visibilities from (u,v)-space to the sky image. Amdahl's law is often cited to illustrate the inherent difficulty of large-scale parallelization [RD13]. As the level of parallelization increases, the runtime decreases only up to the point where serial operations dominate. After this, additional parallelization has very little effect on runtime. However, in our case the level of parallelization can be adjusted to grow at the same rate as the size of the problem (the number of visibilities). For these type of problems (a.k.a. weak-scaling problems), the effect of serial operations is described by Gustafson law, which does not suffer from this saturation [RD14]. The scaling behavior of the ngVLA, described by the parallelization efficiency (the ratio of the actual speedup and the ideal speedup) is a critical parameter for the data processing system. Measuring and optimizing this parameter, considering all relevant serial operations and overheads, is an important activity during the design and development phase of the project.

Other approaches to reduce the cost of data processing are being explored. One of them is applying baseline-dependent averaging. The (u,v)-tracks for long baselines need to be sampled frequently to prevent time-smearing effects. Short baselines, on the other hand, do not need to be sampled with the same frequency. Given that the ngVLA array configuration is concentrated in the core and spans a wide range of baselines, using different integration times can substantially reduce the rate of visibilities that the system needs to process. Similar studies for the SKA suggest that a data rate reduction of ~87% may be possible [RD15]. This strategy can be applied in different places in the system: in the CSP, the CBE, before archive ingestion, or even before post-processing. The choice of implementing baseline-dependent averaging before or after the archive ingestion step dictates if the visibilities are recorded at full time resolution or post-averaging. If the reduction in the data rate is not only necessary to reduce the cost of data processing, but also of archive storage, then averaging before archive ingestion is preferred. However, such an approach does risk limiting the reuse of the short baseline data for other use cases and may limit reprocessing capabilities.

Another strategy is the application of other wide-field corrections algorithms besides w-projection. Preliminary investigations suggest that the use of w-projection in combination with facets for the main array, and the use of w-stacking for some baselines when combining the main array with the long baseline array, can decrease the number of operations with minimal effect on the quality of the final images. This study will continue in the preliminary design phase.

A final approach to constrain the cost of data processing is programmatic. As shown in Table 2, the data rates vary significantly between projects. The most demanding use cases make up only 10% of projected observing time in the ROP, but constitute 88% of the estimated computing requirements [RD05]. The remaining 90% of use cases use cases can be performed with a 6 PFLOPs/second system. Deferring the implementation of these most demanding use cases, or implementing them to partial specification (e.g., limiting imaging dynamic range in low-frequency, full-band, full-beam imaging) may constrain the cost of the computing system within the construction project scope. In all scenarios, limiting the cost of the project will require constraints on the total computing system delivered. Observing time and data reprocessing of these most demanding use cases may need to be constrained in early operations to the projected levels of the ROP or less. Computing resources associated with standard observing modes will need to be treated as finite, and allocated to the highest-ranked projects. This model is analogous to the allocation of observing time, and would use a similar process.

4.6.19.2 NIST Big Data Reference Architecture

The software modules identified in this section define the high-level subsystems required by the offline subsystem to comply with its functional requirements, and it's compatible with the way software systems for the ALMA and VLA observatories have been decomposed. For ngVLA, the interactions between the components belonging to these subsystems, and the technologies they are based on will need to be substantially different than the architectures developed for these observatories in order to meet ngVLA scalability challenges. The data flows that the Offline sub-element needs to ingest and archive, process and provide access for retrieval, visualization and analysis are large enough for the Offline system to be qualified as a Big Data system.

One potential reference architecture for ngVLA is the NIST Big Data Reference Architecture. Reference architectures are blueprints that provide baseline structure to domain-specific application or system designs. Adopting a reference architecture can accelerate design activities, provide a basis for governance that supports coherence and maintainability, and improve communication between stakeholders sharing a common domain model.

As a consequence of the USG's 2012 Big Data Research and Development Initiative, NIST formed a Big Data Public Working Group to create "…a vendor-neutral, technology- and infrastructure-independent framework that would enable Big Data stakeholders to identify and use the best analytics tools for their processing and visualization requirements on the most suitable computing platform and cluster…" In 2019, the working group released the nine-volume NIST Big Data Interoperability Framework. Volume 6 presents a reference architecture for big data systems and is referred to as the NIST Big Data Reference Architecture (NBDRA).

NBDRA consists of a conceptual model, five roles, two fabrics, an Activities View describing activities performed by the roles, and a Functional Component View describing classes of components that carry out activities. Figure 55 shows the conceptual model encompassing the roles and fabrics.

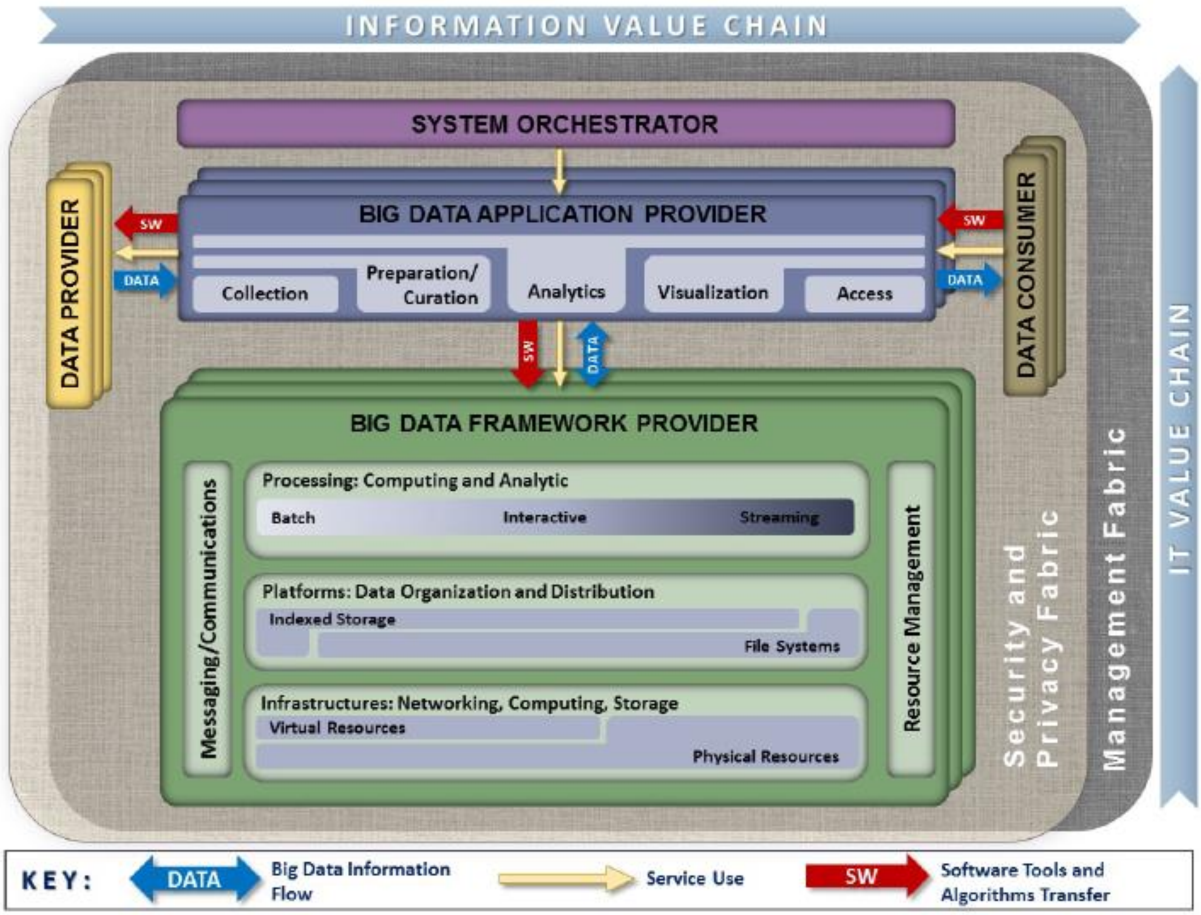

Figure 55: NIST Big Data Reference Architecture (NBDRA).

The System Orchestrator, Data Provider, Application Provider, Framework Provider, and Data Consumer constitute the five conceptual roles that exist in every Big Data system. The System Orchestrator (SO) configures and manages other components to implement one or more workloads the architecture is designed to execute. The SO may also collaborate with the Management Fabric to monitor workloads, confirm quality of service requirements, and elastically provision resources to meet workload requirements. The Data Provider (DP) introduces new data feeds into the system. The Application Provider (AP) executes the set of operations alluded to in the figure to meet the requirements of the SO, as well as security and privacy requirements. The Framework Provider (FP) typically consists of one or more hierarchically organized processing, data, and infrastructure frameworks. Data Consumers (DC) are humans or systems that use AP interfaces or services to access data of interest. DC activities include: search and retrieve, download, analyze locally, generate reports, and visualize. Within a given Big Data Architecture implementation, there may be multiple instances of elements performing the DP, DC, FP, and AP roles including multiple Big Data applications which use different frameworks to meet requirements.

Fabrics provide services to the main roles and represent the interwoven nature of management, security, and privacy concerns with the rest of the system. The Management Fabric encompasses two general groups of activities: system management and Big Data life cycle management (BDLM). System management activities are shown in Figure 56 below.

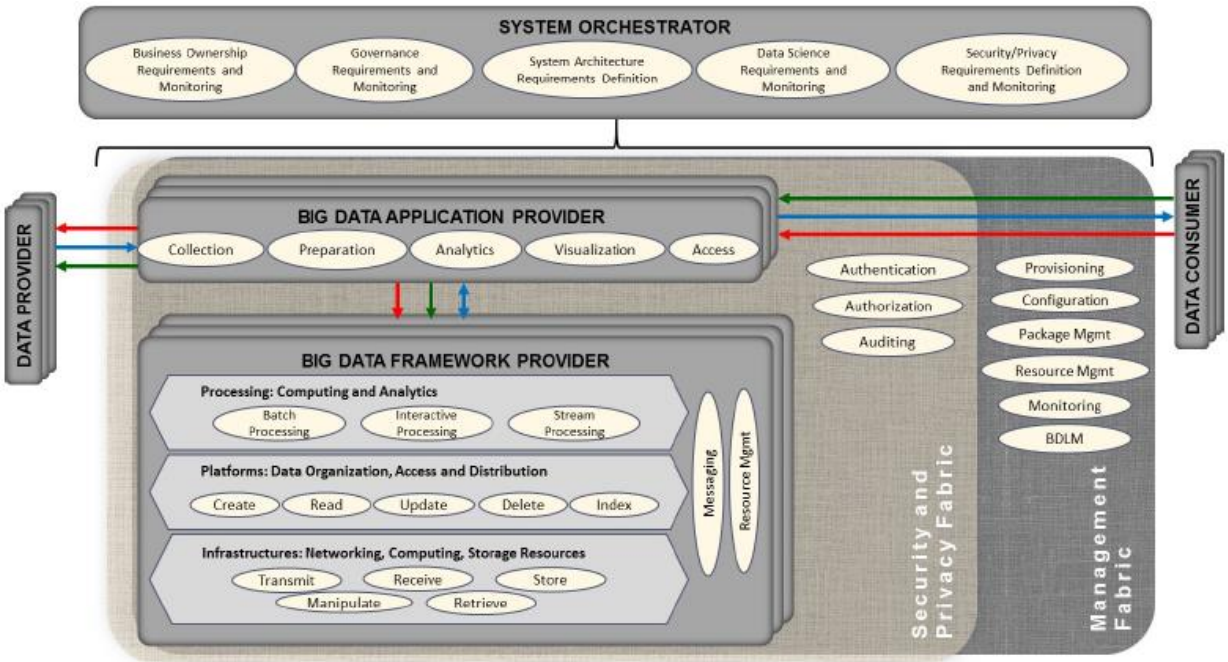

Figure 56: Top-level classes of Activities within the Activities View.

BDLM activities include collection, preparation/curation, analytics, visualization, and access.

The Functional Component View, shown in Figure 57 below, shows the components that perform the activities outlined in the activities view.

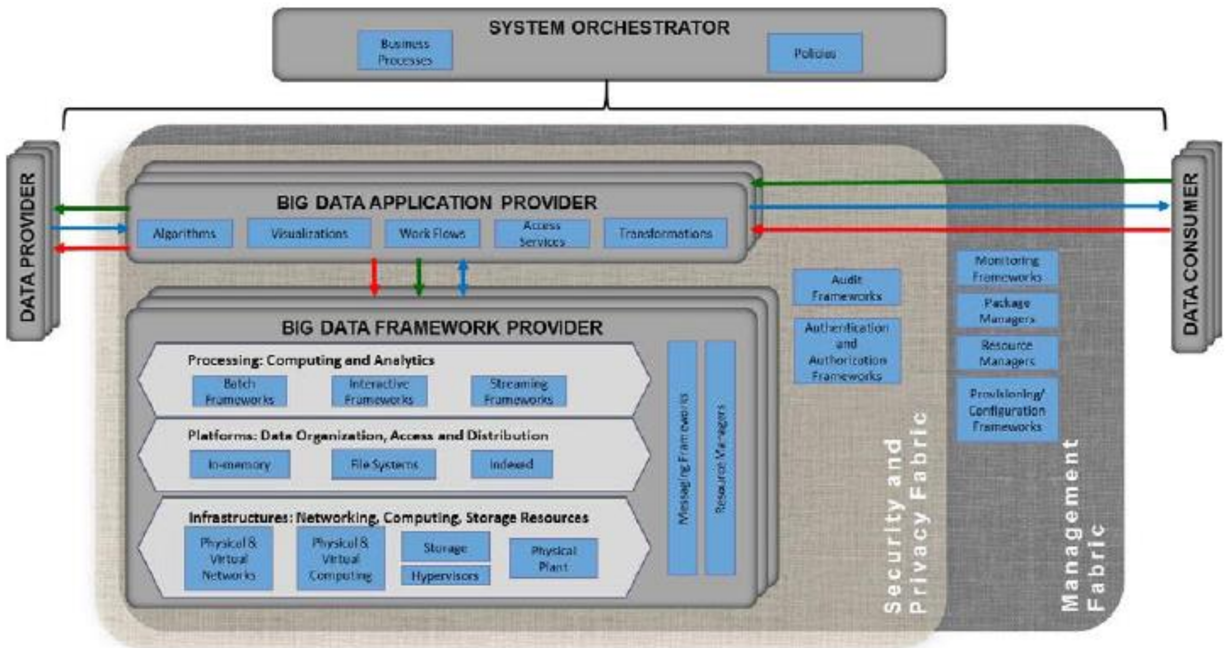

Figure 57: Common classes of functional components.

Activities and functional components need not map one-to-one, many functional components may be required to execute a single activity, and multiple activities may be performed by a single functional component. The activity and component views help maintain a mapping of activities to functional components to verify that all activities can be performed by some component and that only components that are necessary are included within the architecture.

4.6.20 Maintenance and Support Subsystem (MSS)

The systems that compose the Maintenance and Support Subsystem are shown in Figure 58.

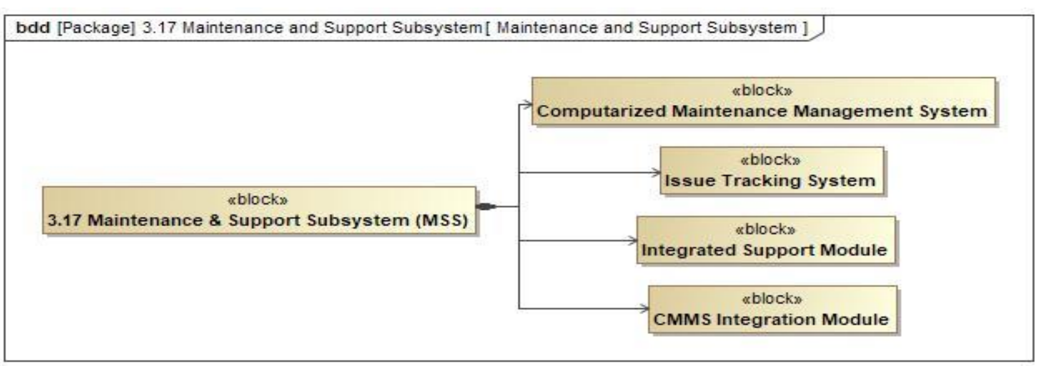

Figure 58: High-level decomposition of the Maintenance and Support Subsystem.

The MMS components are:

(a) **CMMS Integration Module**: This integrates the Engineering Database with the CMMS system. Given that the CMMS system most probable be a COTS component, it is foreseen that some adaptation may be required between this system and the Engineering Database. The CMMS system will include automated diagnostics and failure prediction functionality.

(b) **Computerized Maintenance Management System**: This COTS software package maintains a database on observatory maintenance operations. This system provides several functions aimed to effectively organize maintenance operations, between them the implementation of predictive maintenance algorithms, condition-based monitoring, and asset management.

(c) **Integrated Support Module**: This module provides a centralized interface for support personnel to gather troubleshooting information, such as logs, alarms, and monitoring data.

(d) **Issue Tracking System**: This COTS software maintains lists of issues and helps organize activities needed to resolve them. This may be provided by issue tracking system already in use by NRAO.

4.6.21 Data Stores (DST)

The data stores included in this package are logical and are deployed into physical storage systems and databases depending on their requirements. They may be consolidated or segregated as necessary.

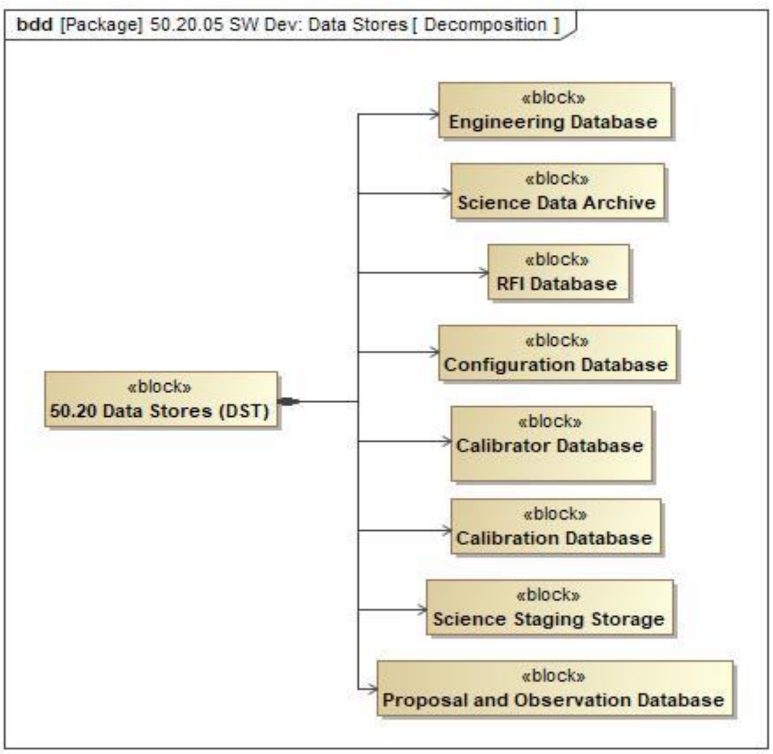

Figure 59: Decomposition diagram of the DST subsystem.

This diagram above shows the databases and data storage systems included in DST:

(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) **Configuration Database**: This database contains the configuration data necessary to bring the telescope to an operational state. It includes software configurations, hardware parameters that need to be loaded into hardware devices, user preferences, etc. Note that these configuration data don't include the calibrations managed in the Calibration Database, although there could be interdependencies between these databases, or they could be integrated.

(d) **Engineering Database**: A database to support engineering operations, storing data such as monitoring streams, alarms, and system logs. For a system like the ngVLA, these data have specific scalability requirements. A time-series database such as InfluxDB (http://influxdata.com) may be adequate, although the decision is deferred for later design stages.

(e) **Proposal and Observation Database**: This contains science proposals and scheduling blocks along with associated data structures such as source catalogs, user information, and telescope capabilities.

(f) **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.

(g) **Science Data Archive**: The science data includes visibility files, calibration tables, images, cubes, catalogs, pulsar profiles, etc. along their associated meta-data.

(h) **Science Staging Storage**: Storage area that stages science data while it is being transferred to the Science Data Center.

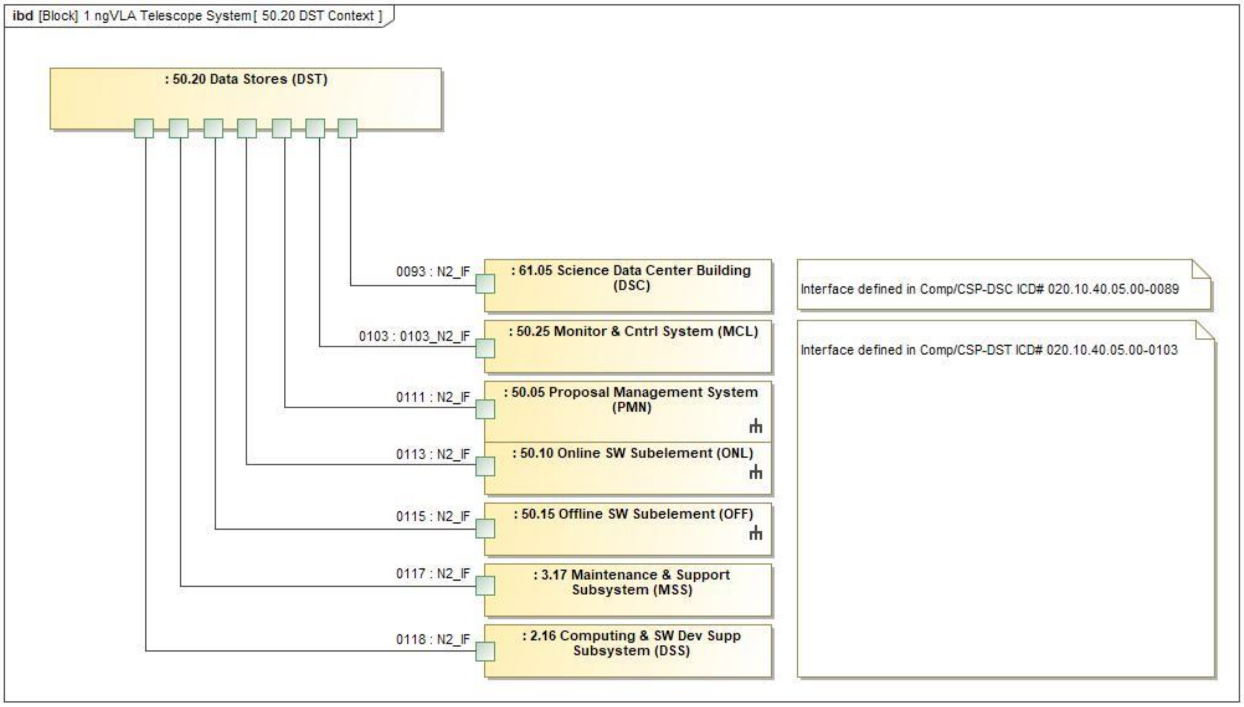

Figure 60: Context diagram for the DST subsystem

The DST external interfaces are:

(a) 0093 - Interface with the Science Data Center Building (DSC): This interface specifies requirements of rack space, power, cooling, etc., for the computing equipment that will hold the databases and data storage systems included in DST.

(b) 0103, 0111, 0113, 0115, 0117, 0118: These are all data access interfaces (e.g. SQL, REST interfaces) between DST and other subsystems that use the data stored within this subsystem.

4.6.22 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.

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 central processing facility 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.

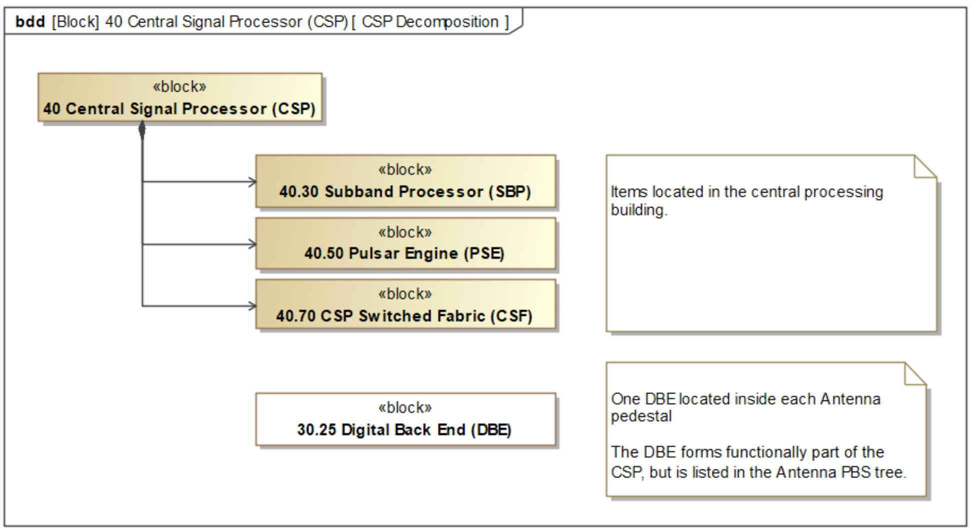

Figure 61: CSP product breakdown

The external interfaces of the DBE are shown in Figure 62 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 RTD.

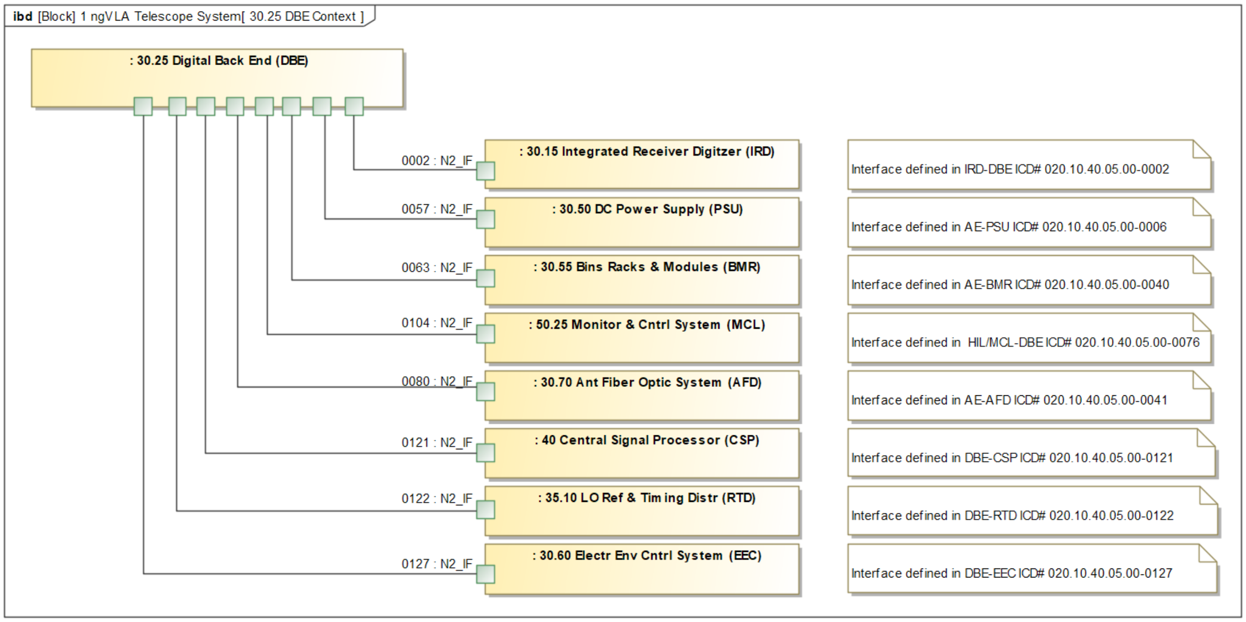

Figure 62: DBE external interfaces

The external interfaces of the central CSP components are shown in Figure 63:

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.

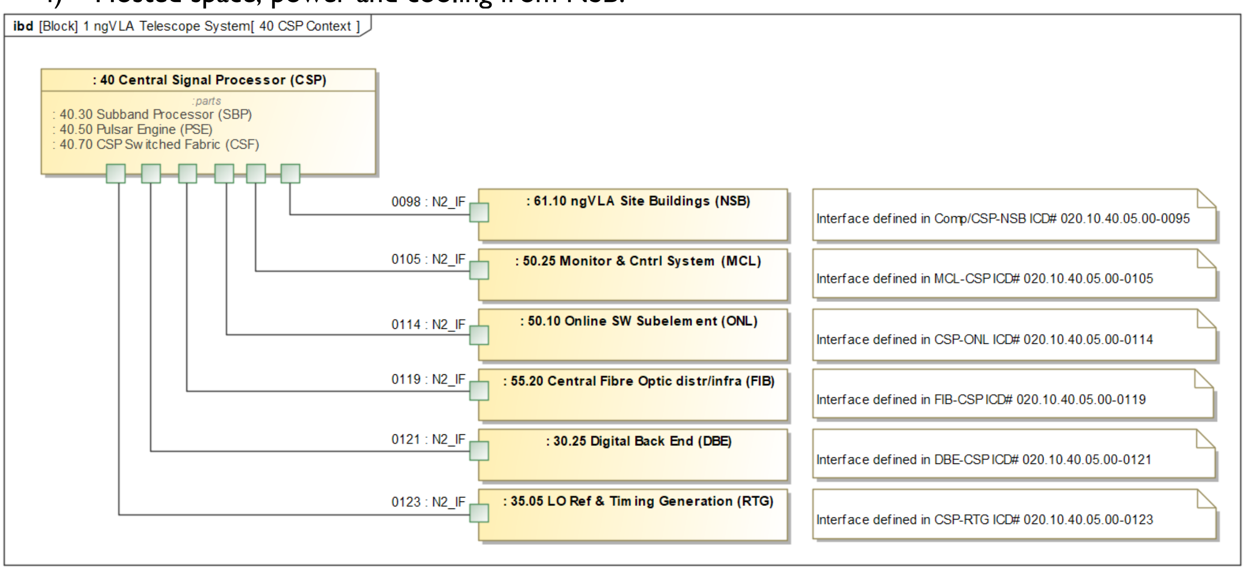

Figure 63: CSP external interfaces

4.6.23 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.
   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.

The decomposition of this subsystem is shown in Figure 64 below.

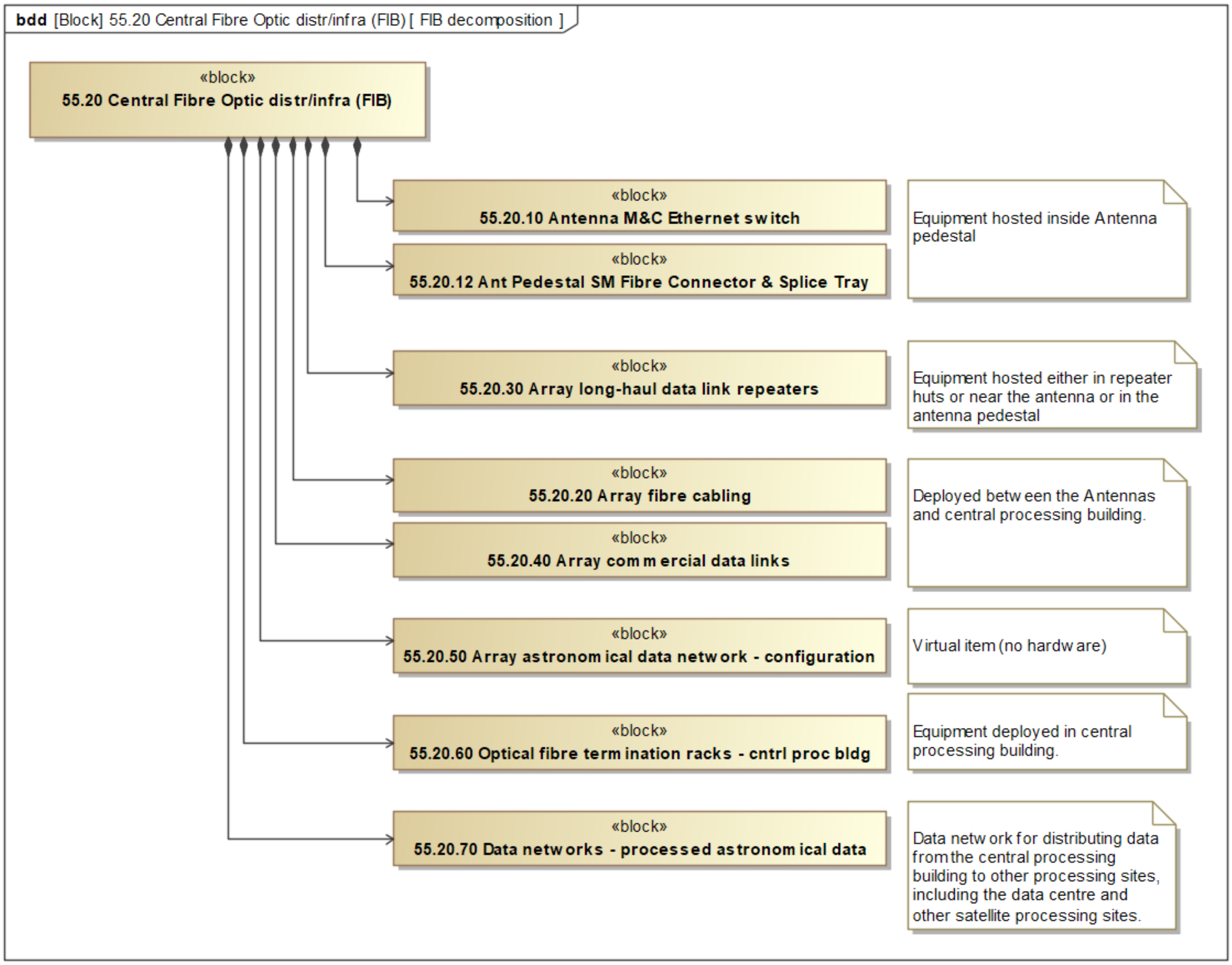

Figure 64: FIB decomposition

FIB has interfaces to the following subsystems, as shown in Figure 65:

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 OFF 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.

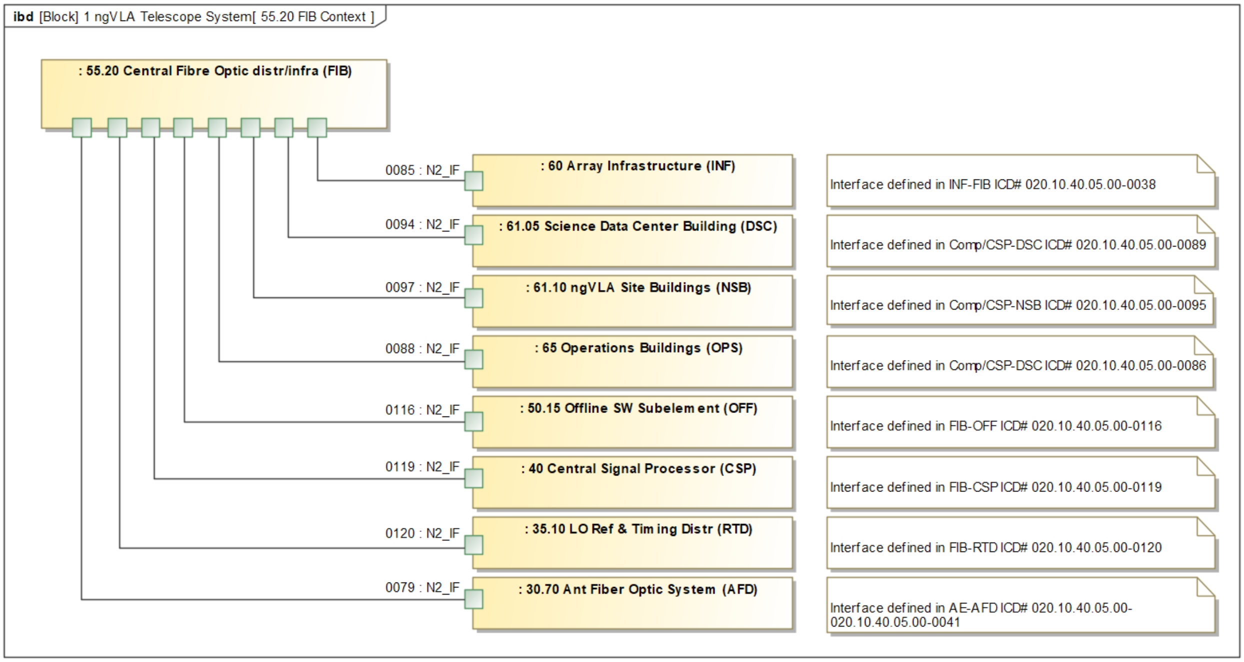

Figure 65: FIB external interfaces

4.6.24 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.

The interfaces of the RTG to other subsystems are shown in Figure 66:

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.

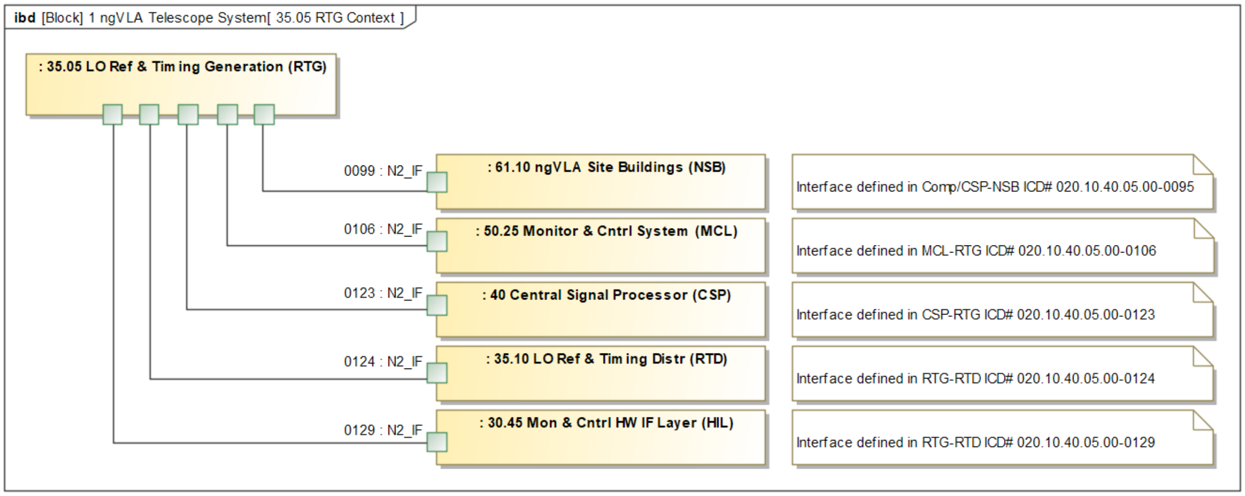

Figure 66: RTG decomposition and external interfaces

4.6.25 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.

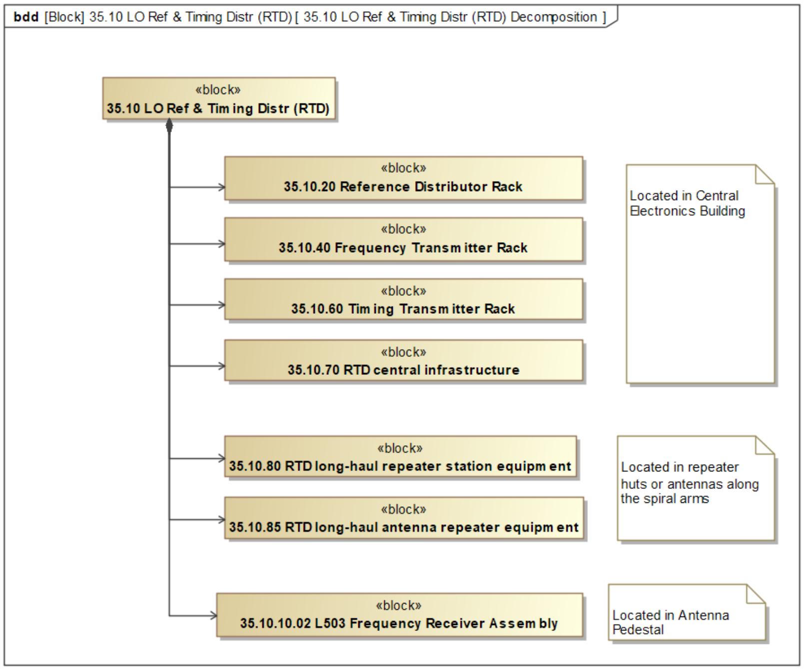

Figure 67: RTD decomposition

The RTD interfaces to the following subsystems as shown in Figure 68:

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.

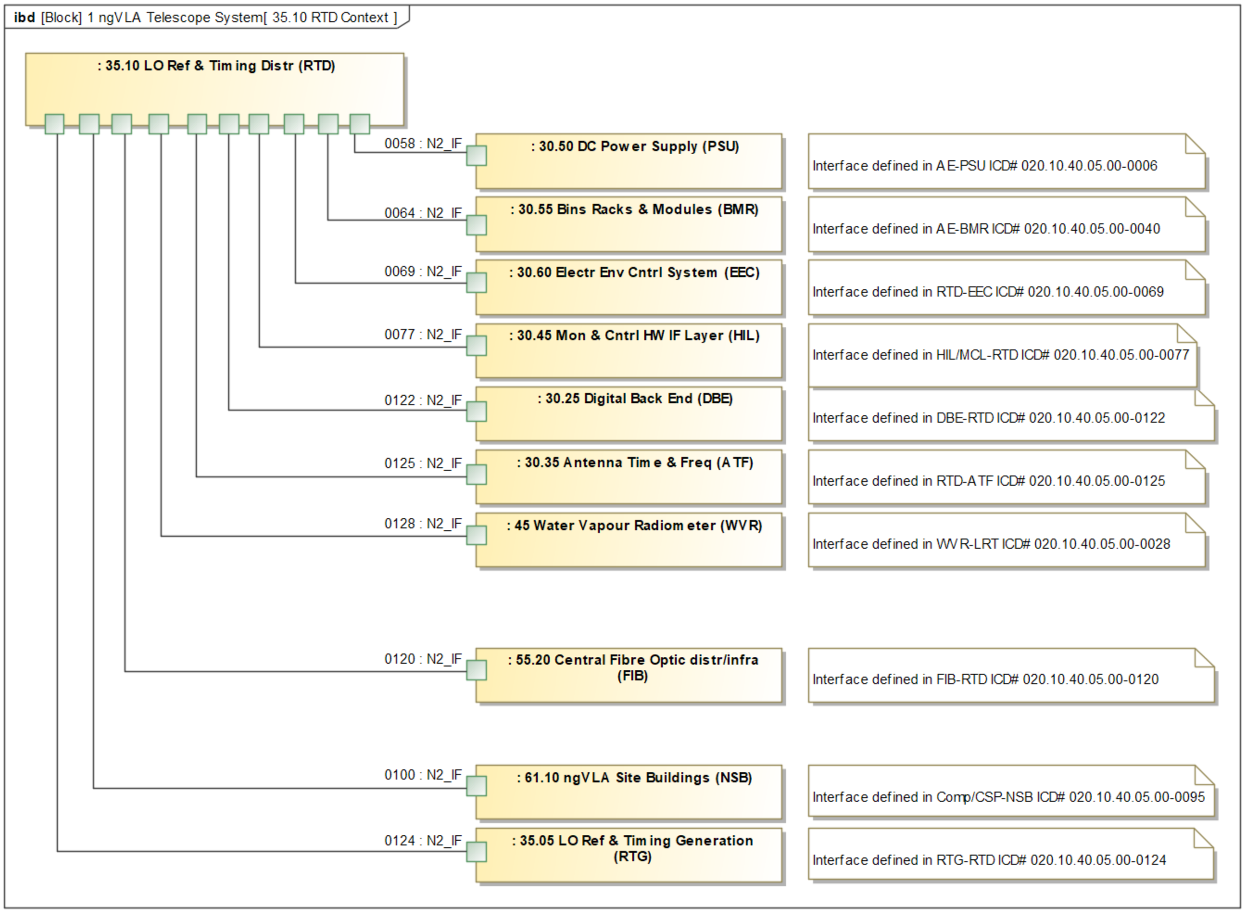

Figure 68: RTD context

4.6.26 Antenna Time and Frequency (ATF)

The ATF performs the local distribution of reference timing and frequency signals for all components located on the Antenna (except the DBE, which is supplied by the RTD). 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 69 below. The Repeater equipment is shown for context, but is part of the RTD subsystem.

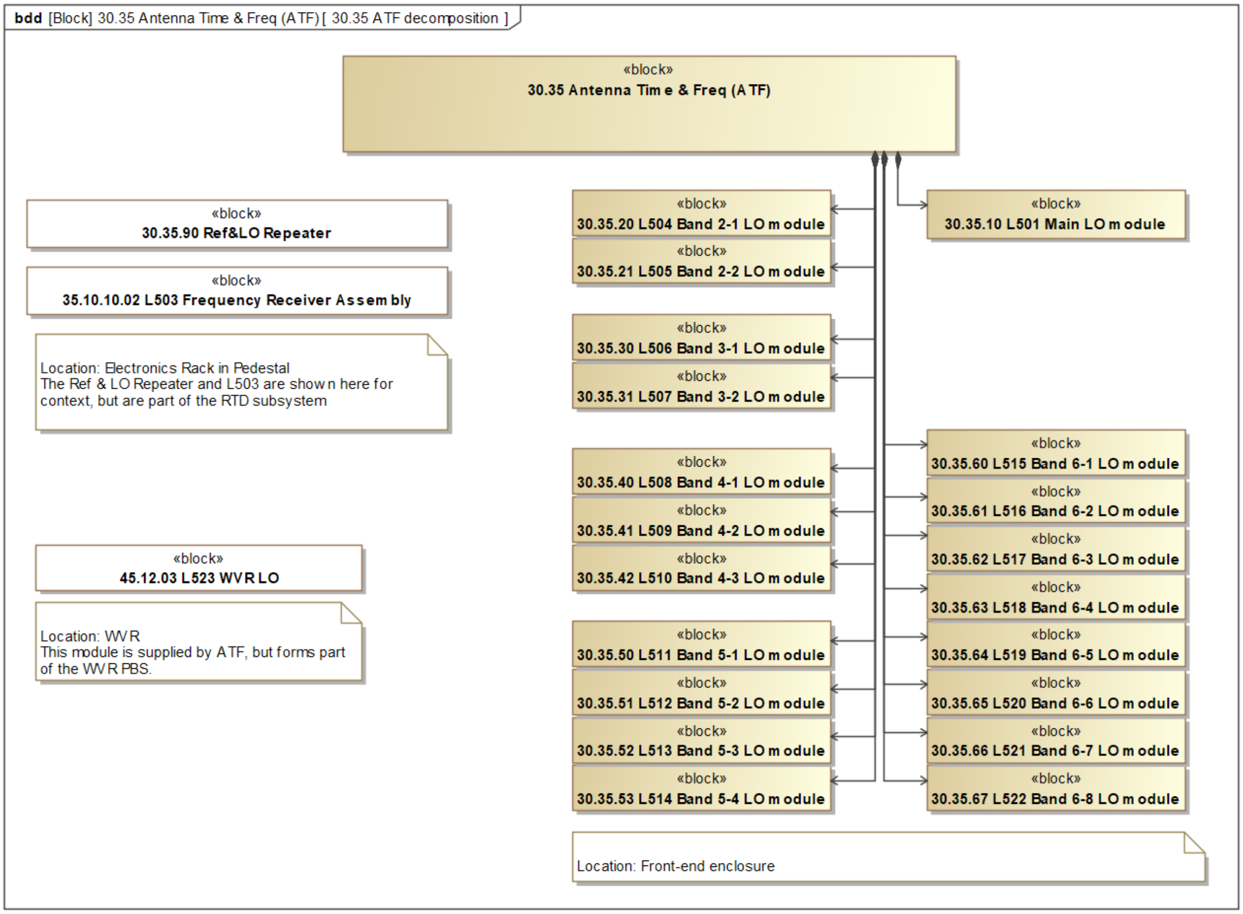

Figure 69: ATF decomposition

The external interfaces of the ATF are shown in Figure 70 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.

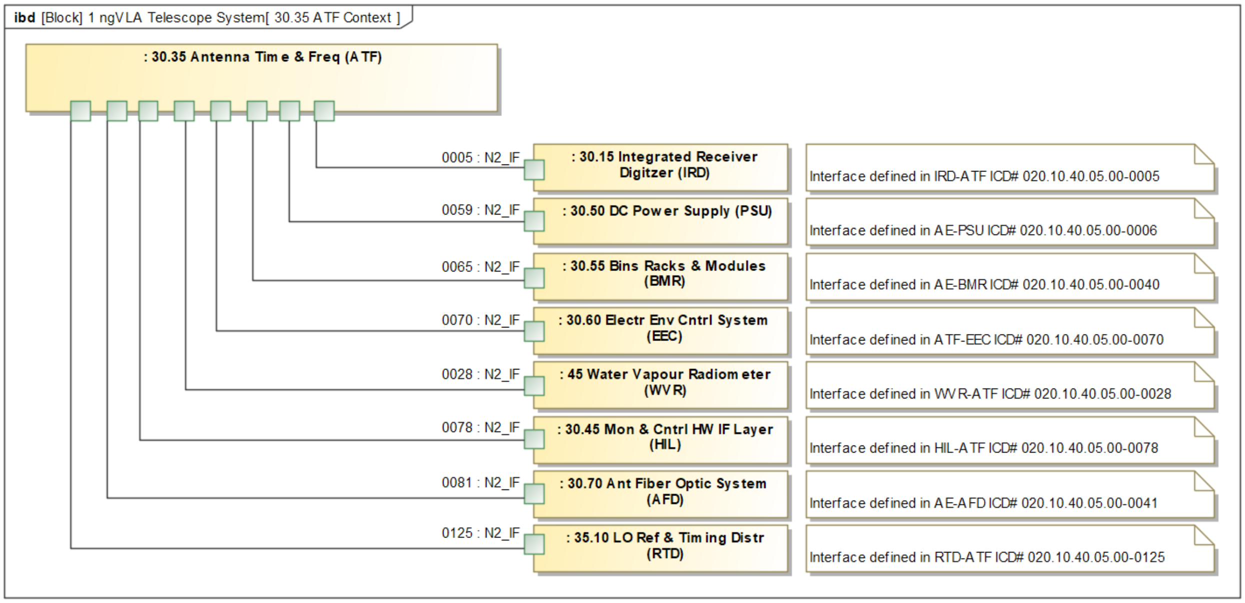

Figure 70: ATF external interfaces

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 nine functional operating modes that are required:

1. Interferometric Mode
2. Phased Array Mode
3. Pulsar Timing Mode
4. Pulsar and Transient Search Mode
5. VLBI Mode
6. Total Power Mode
7. On-the-Fly Mapping Mode
8. Solar Mode
9. Concurrent Interferometric and Phased Array 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 71 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.

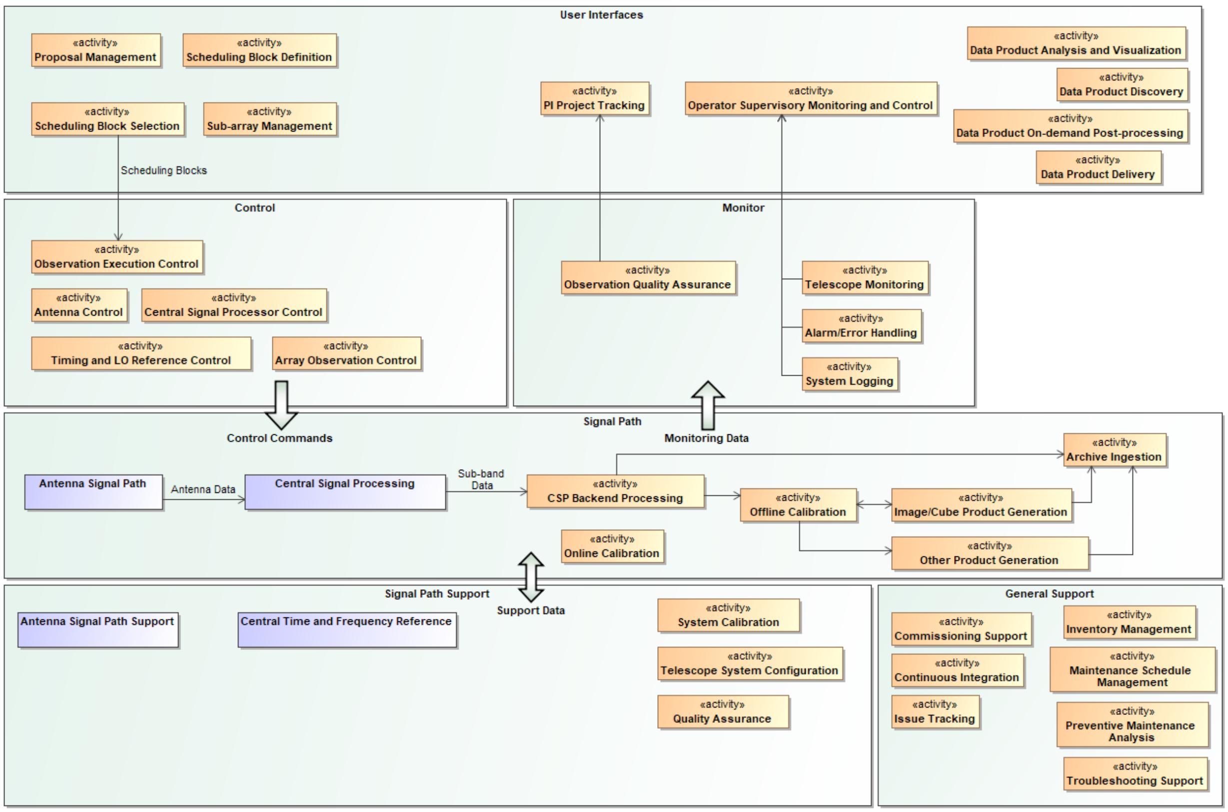

Figure 71: System Functions

Each of the functions shown in Figure 71 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 71) 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 72. 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.

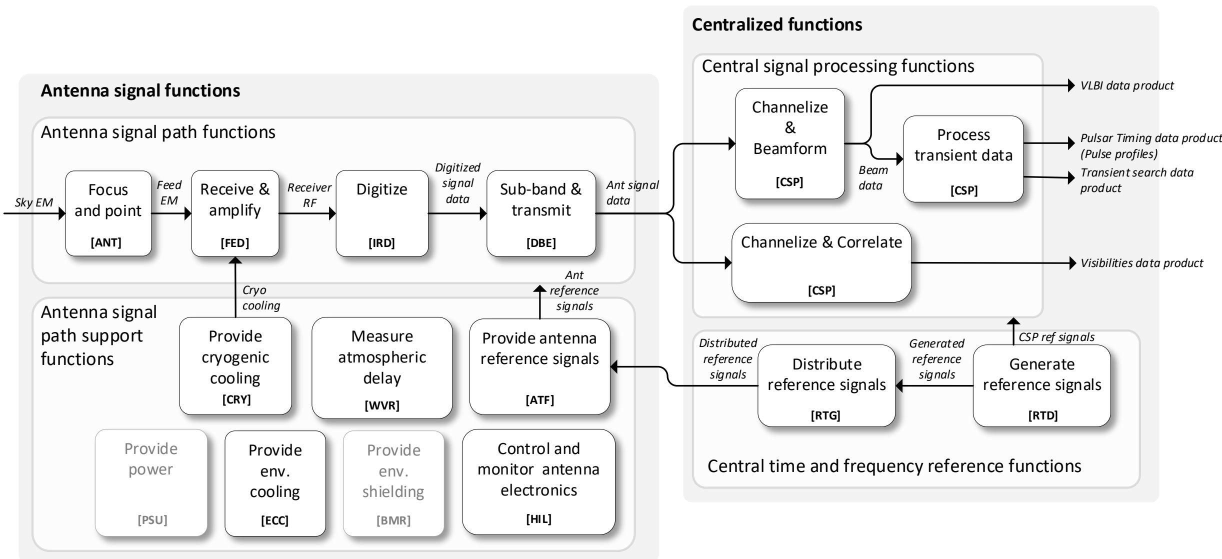

Figure 72: Signal path functions

5.2.2.1 Antenna signal path: Focus and point

The focus and point functions are implemented by the Antenna as shown in Figure 73.

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.

The second primary function is to point the antenna. The antenna pointing model is configured and implemented external to the antenna (by the M&C software), so the pointing commands applied by the antenna are fully corrected and time tagged Azimuth and Elevation pointing polynomials. To apply these pointing commands correctly, the antenna needs an accurate absolute time reference which it receives through the M&C 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 M&C system 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.

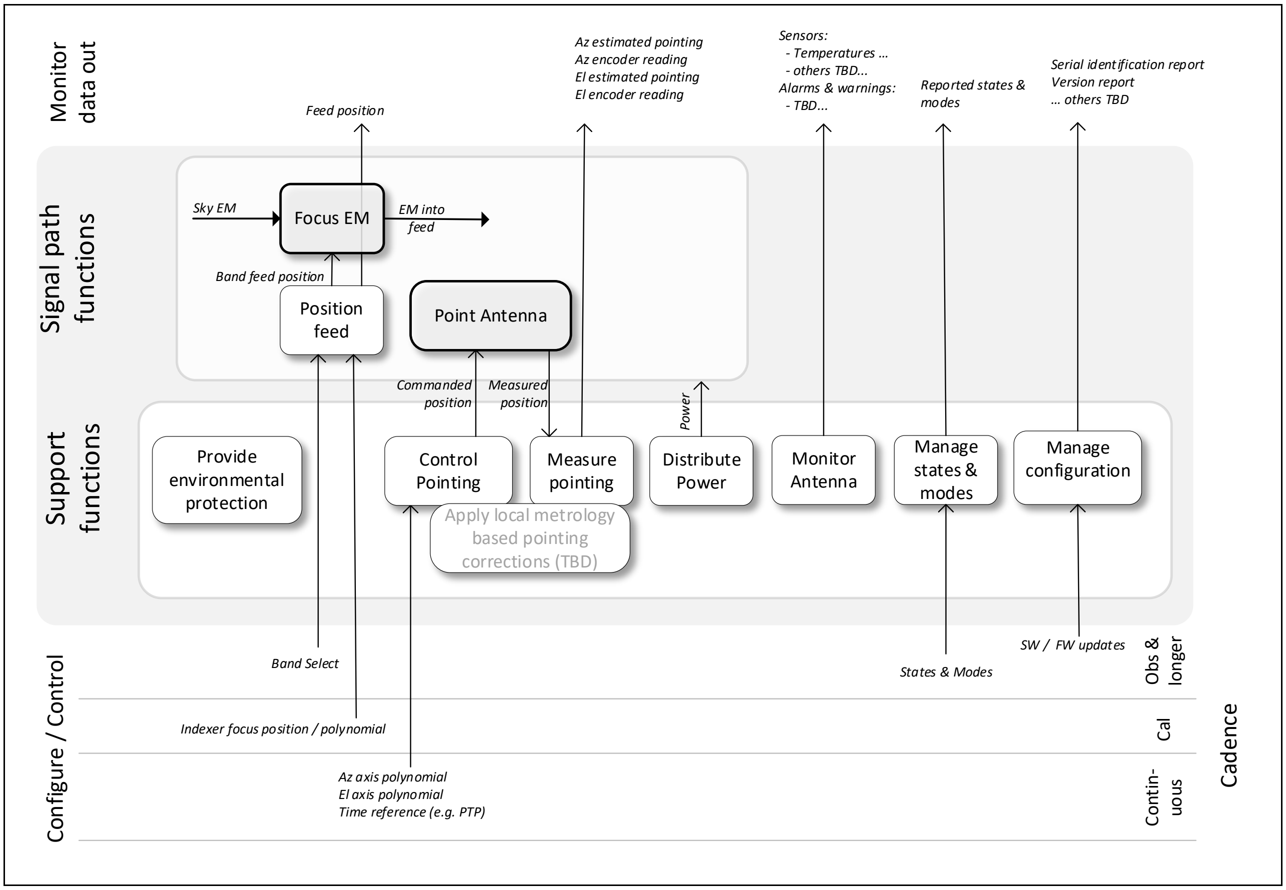

Figure 73: Focus and point functions

5.2.2.2 *Antenna signal path: Receive and amplify*

The functional flow diagram in Figure **74** 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 M&C interface.

The received signal is amplified by cryogenically cooled low-noise amplifier (LNA) per polarization, with LNA bias levels configurable via the M&C 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 M&C system. 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.

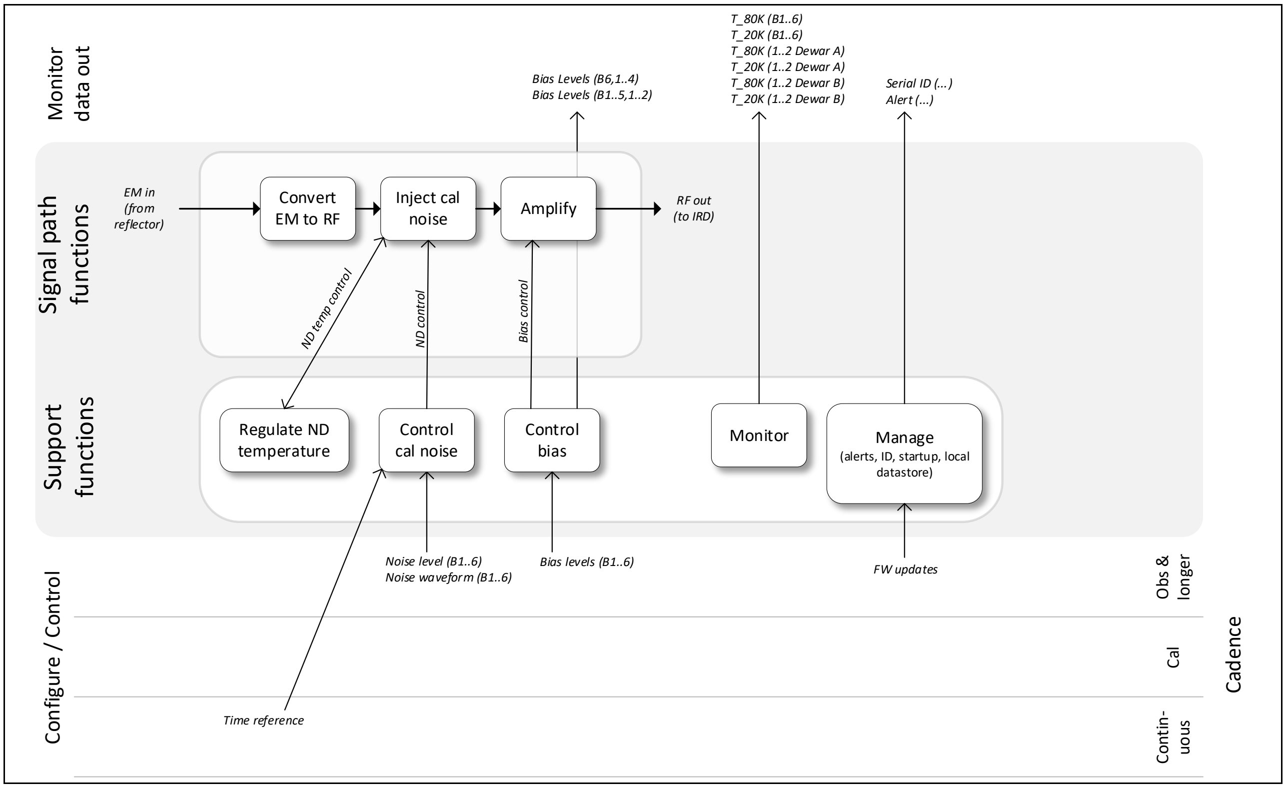

Figure 74: Receive and amplify functions

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 75.

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 M&C network.

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 M&C system 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.

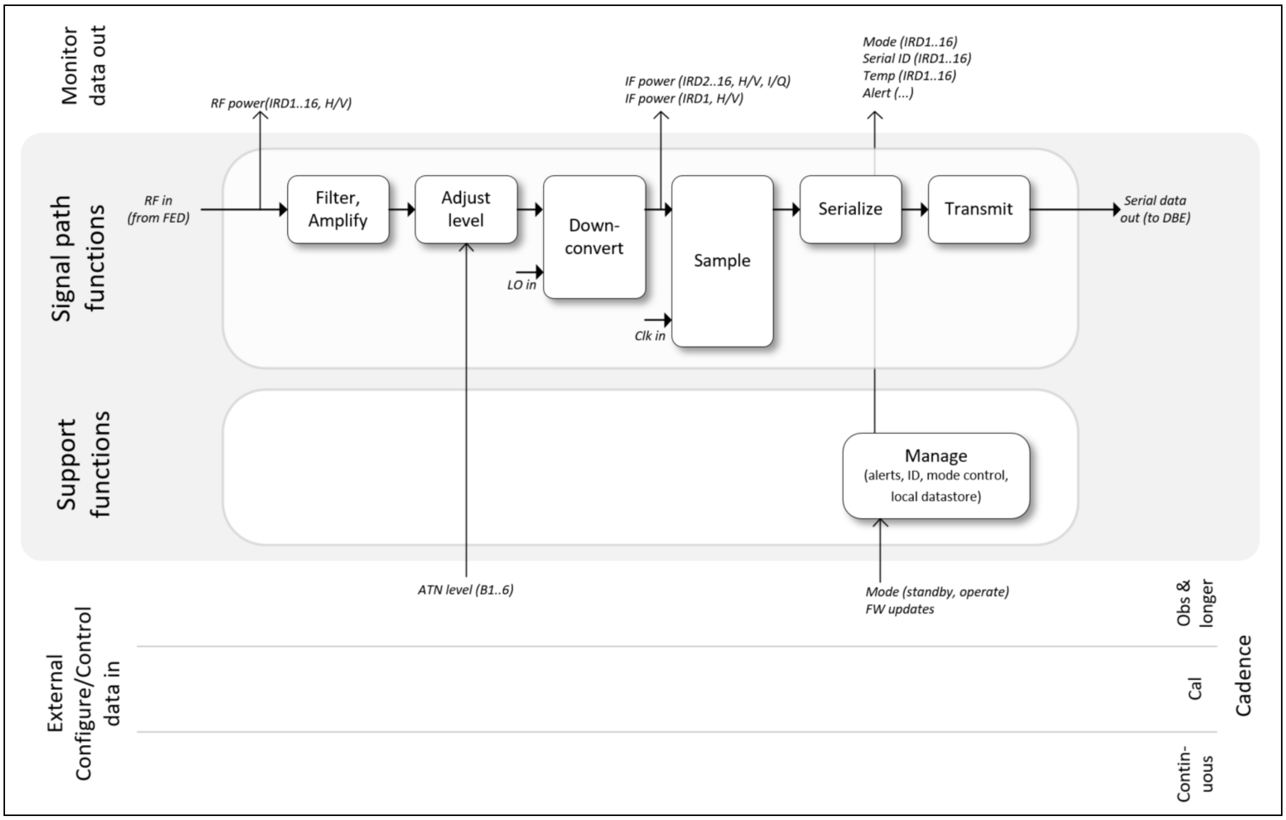

Figure 75: Digitize function

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 76.

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 time domain digital sideband separation operation on the incoming signal using a FIR filter to correct for this leakage. The details of the design and rationale for this 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 M&C network.

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

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 each by means of a Polyphase Filter Bank. 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 M&C 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.

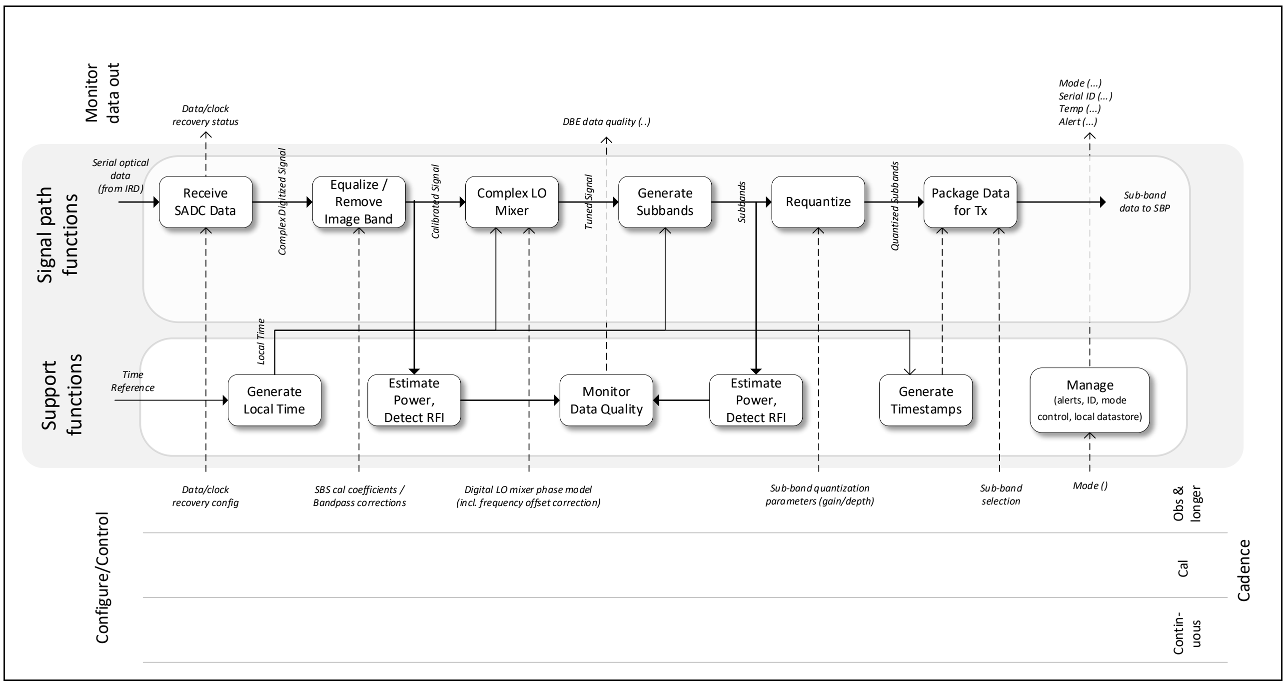

Figure 76: Sub-band and transmit functions

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 Sideband 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 a 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 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 M&C network 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.

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

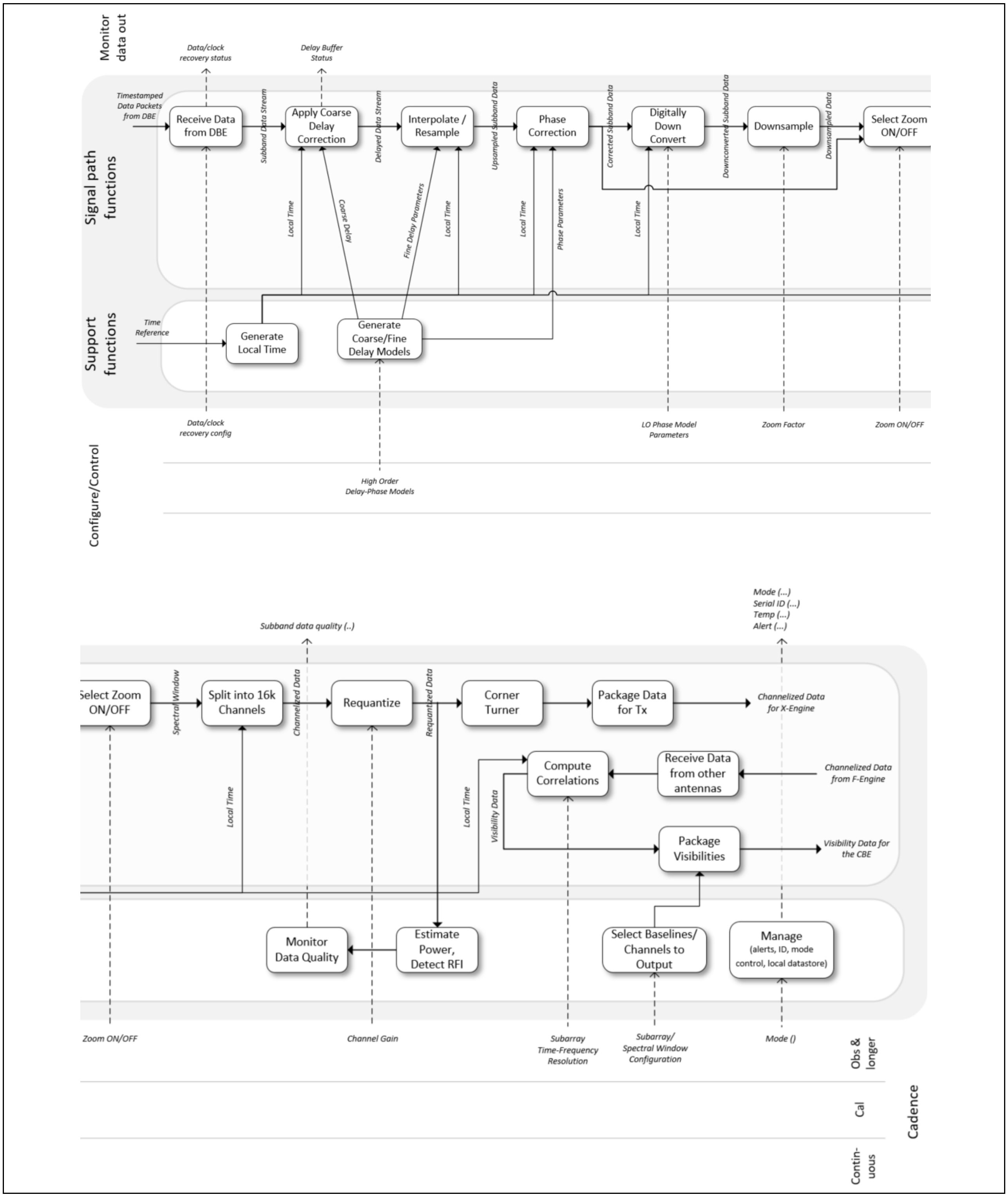

Figure 77: Channelize and Correlate function

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 M&C network. 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.

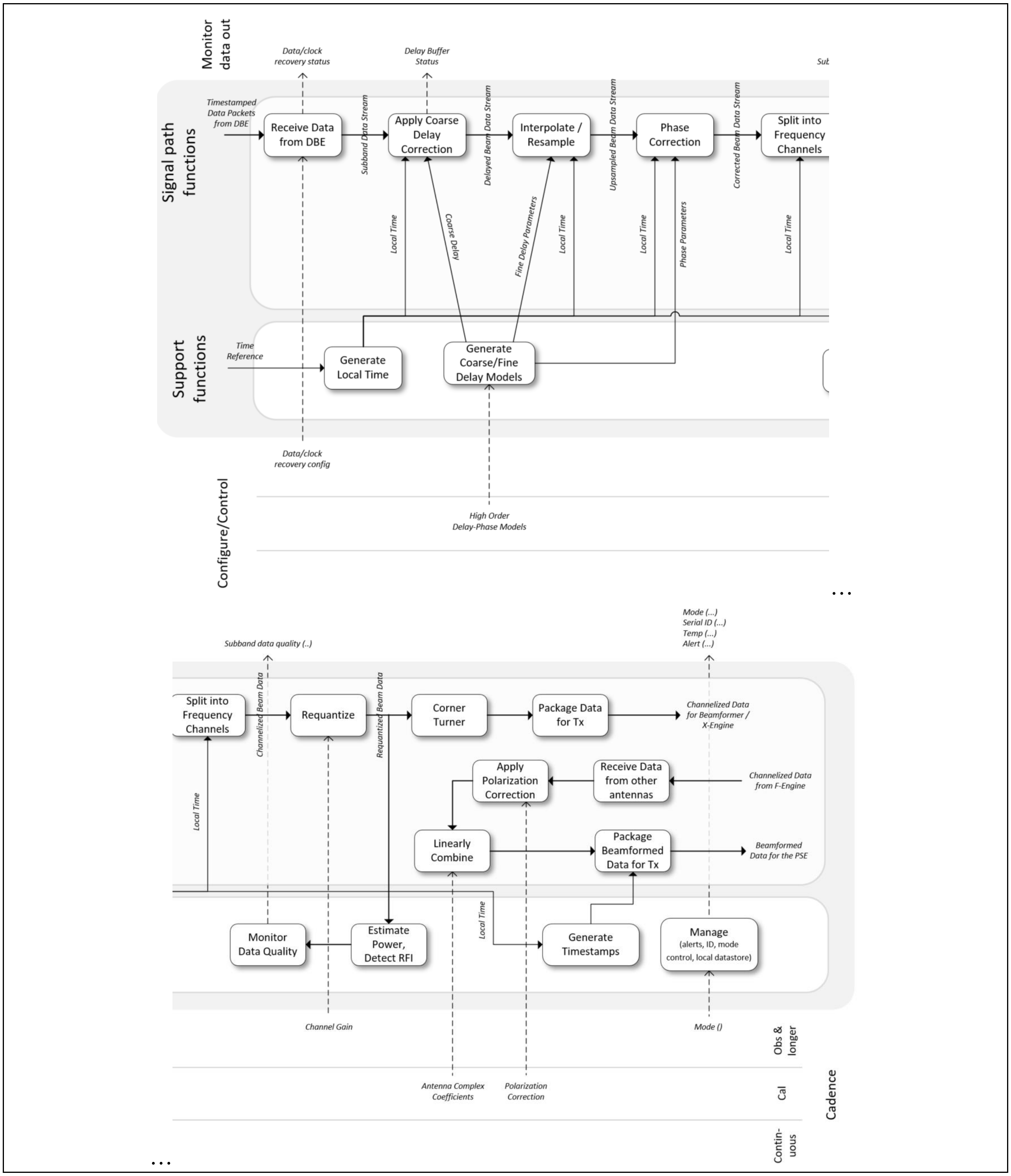

Figure 78: Beamforming functions

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 M&C. 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.

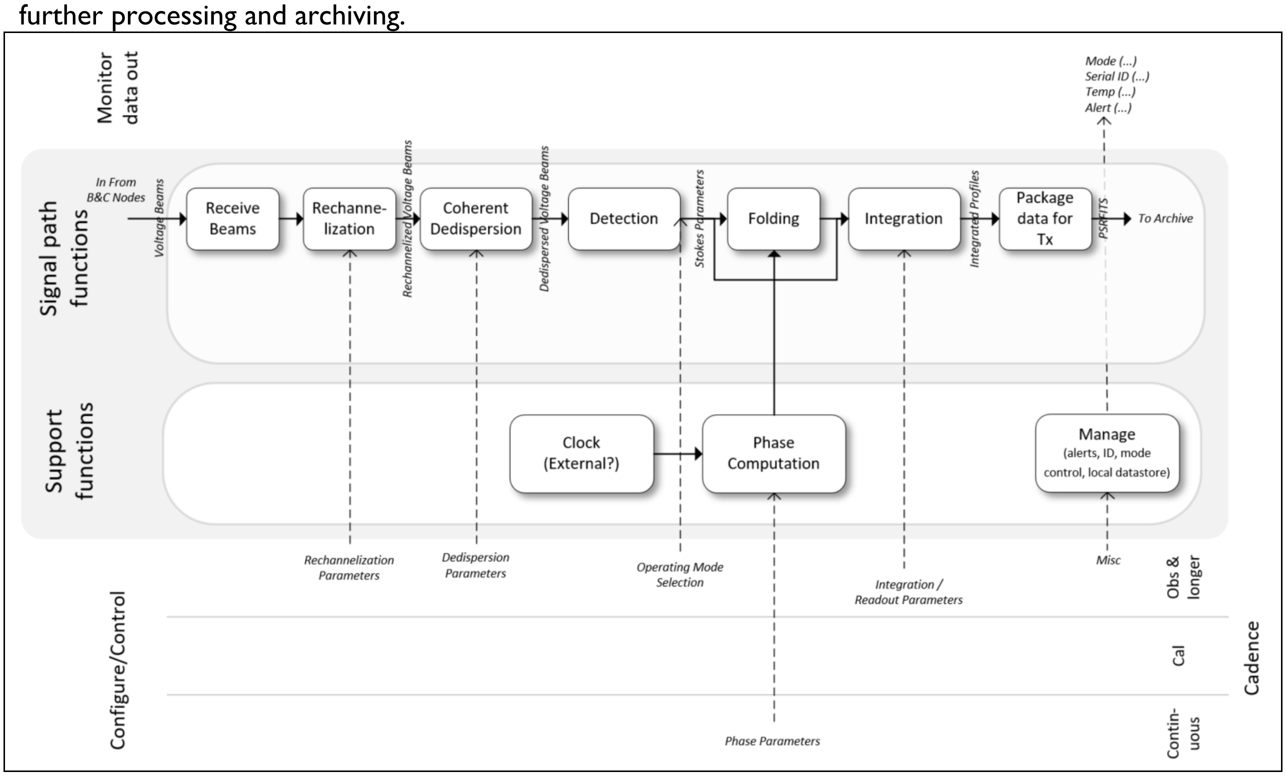

Figure 79: Transient processing functions

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 80. The various sensor data is streamed via the M&C network 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 80. 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.

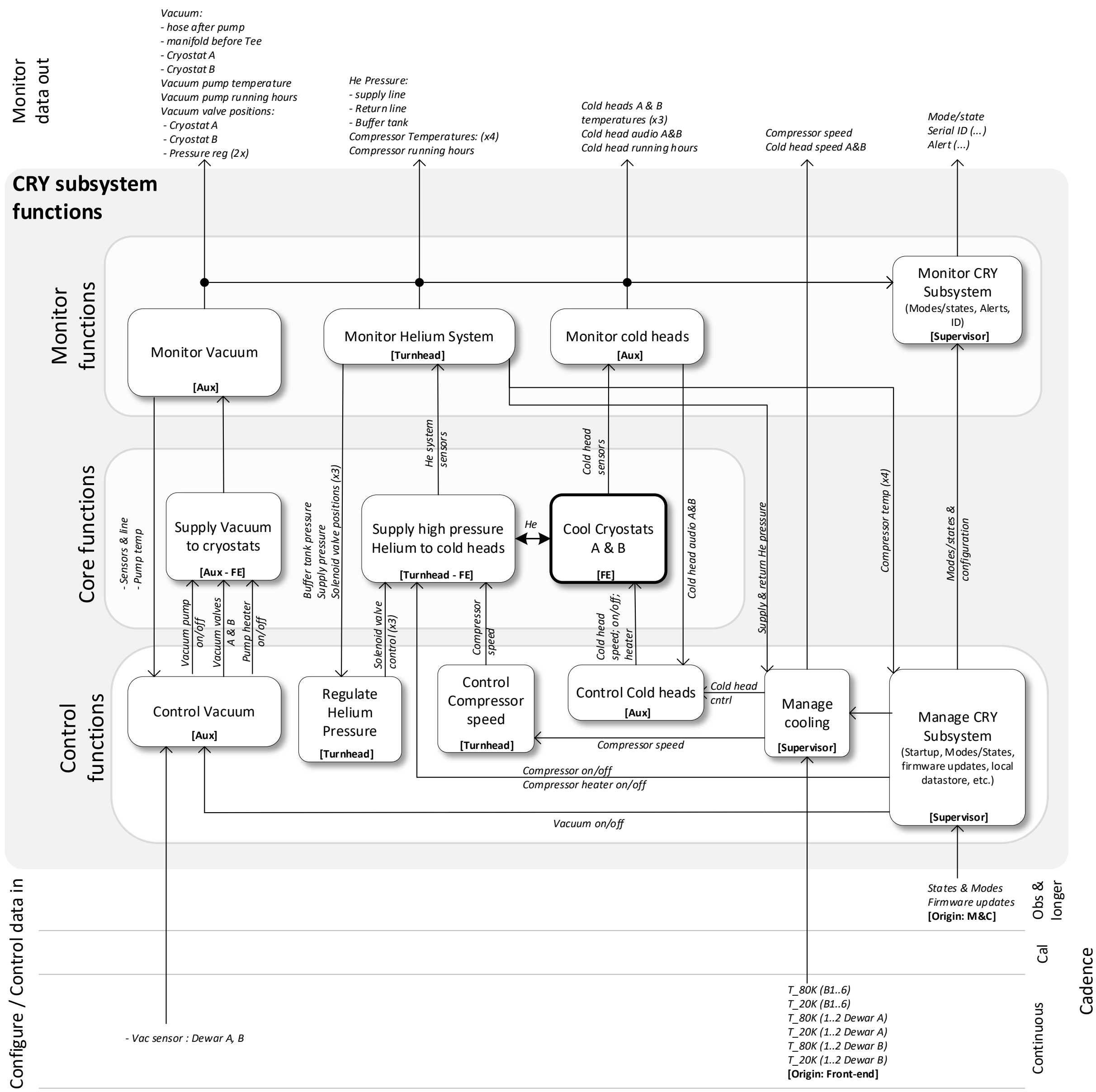

Figure 80: Cryogenic cooling function

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 81 below.

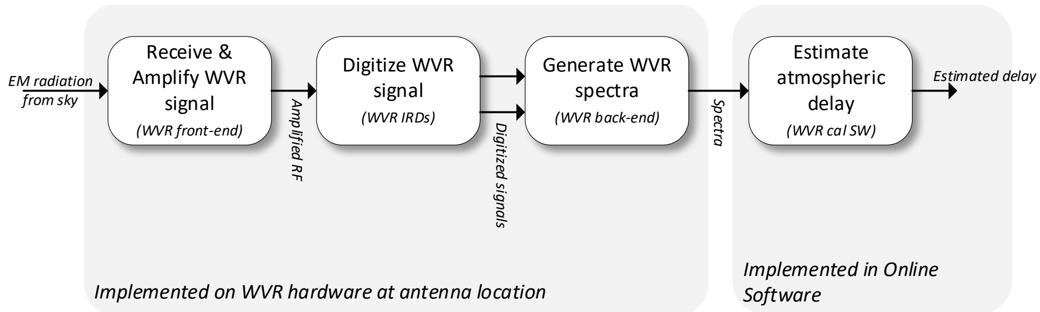

Figure 81: WVR functions overview

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 82. 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.

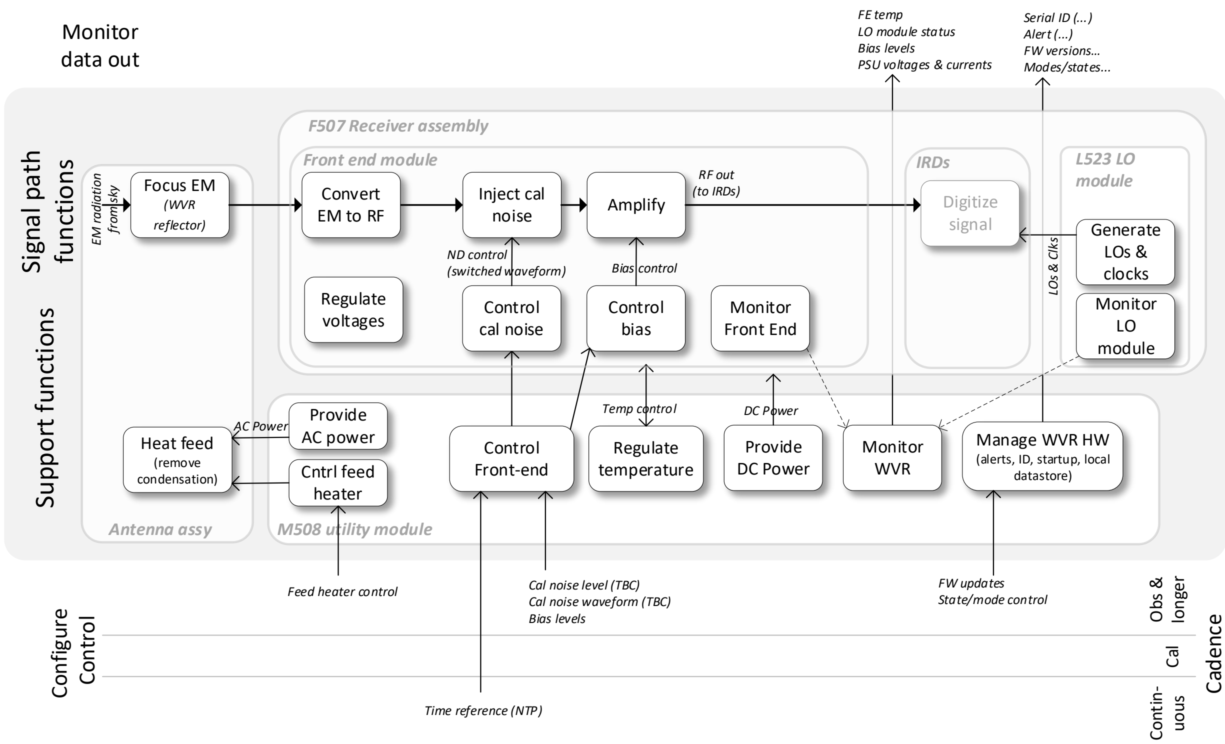

Figure 82: Receive and amplify WVR signal functions

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 83. 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.

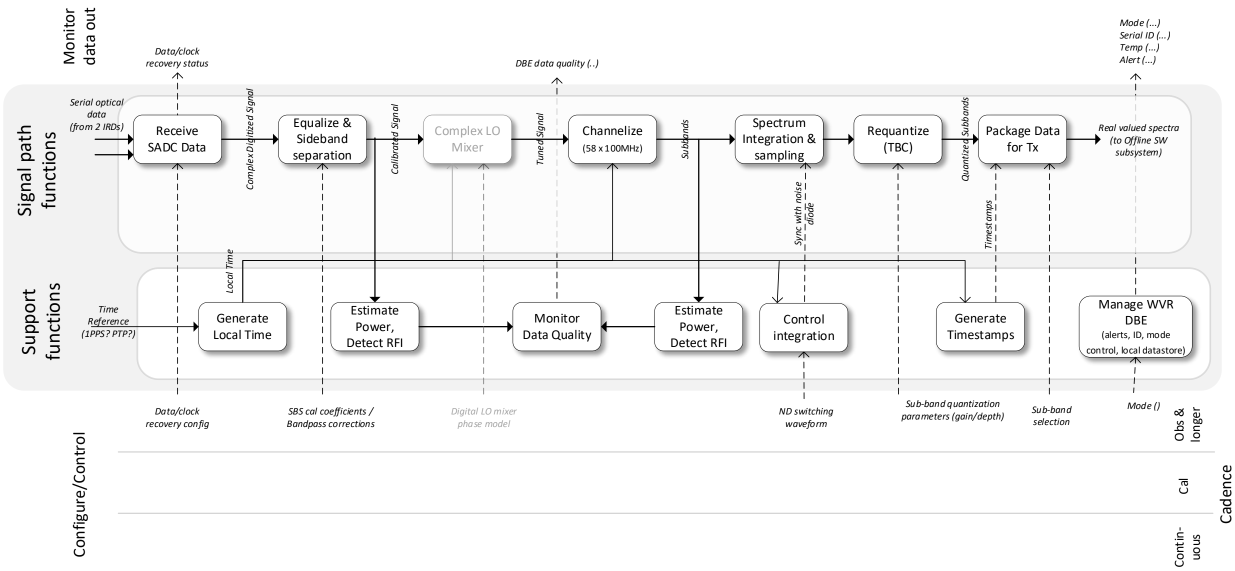

Figure 83: Generate WVR spectra functions

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 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 the centralized the correlation, beamforming and transient processing functions.
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.

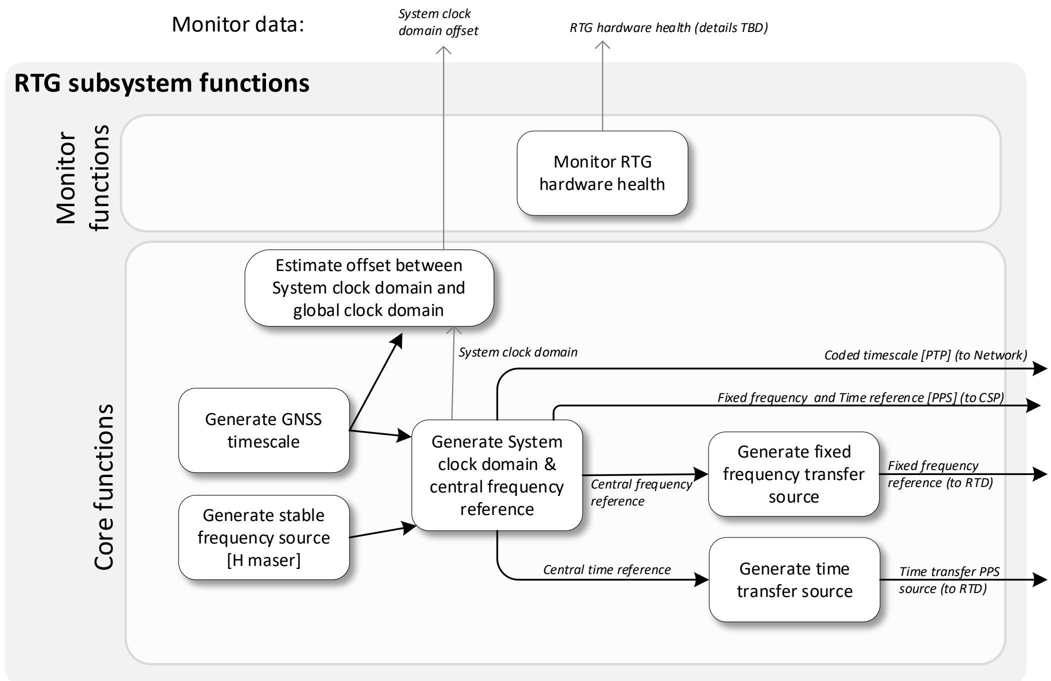

Figure 84: Reference signal generation functions

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 LBA antennas and antennas that are not directly connected by fiber. The number of connected antennas is designated with (N) in Figure 85.

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 from the received frequency reference by dividing the frequency reference by its frequency to produce a PPS. The Antenna domain clock is transmitted to the DBE where it is used for time stamping the astronomical signal data.
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 system.

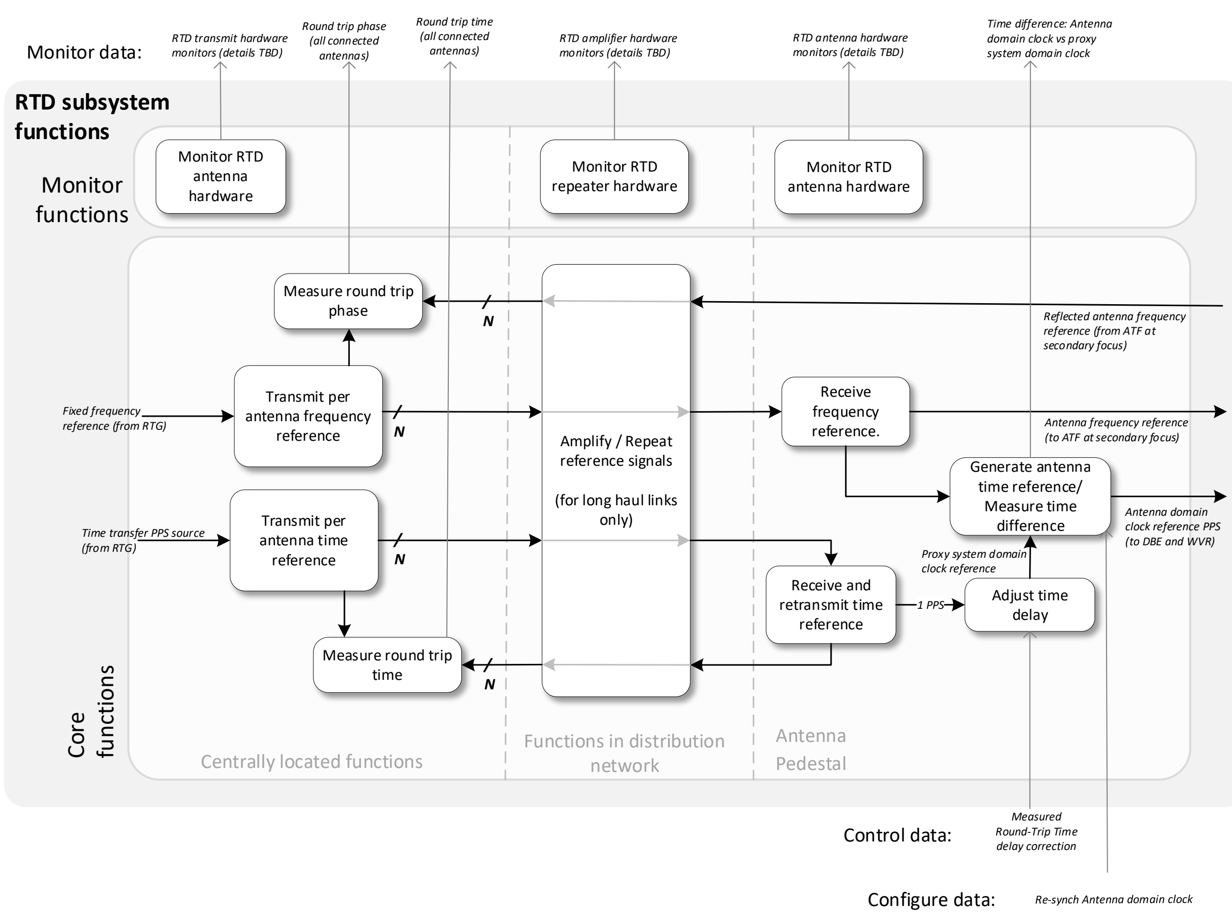

Figure 85: Reference signal distribution functions

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 control and monitoring 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 **86**:

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.

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 **86**. The ATF supports the remote update of firmware.

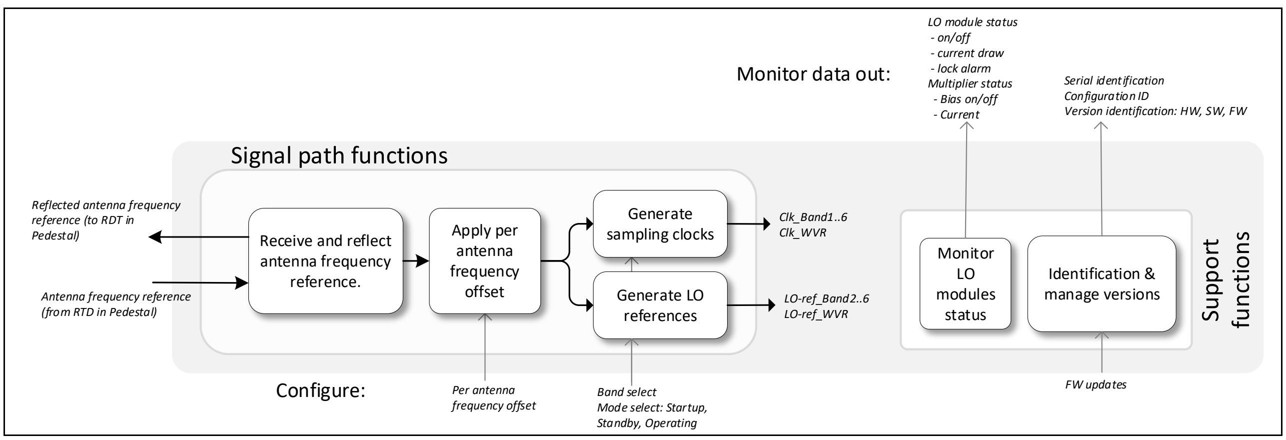

Figure 86: Antenna time and frequency reference function

5.2.4 Software Functions: Signal Path Functions

The software signal path functions are:

(a) **Archive Ingestion**: As an observation proceeds, the Correlator Back End and the Metadata Capturer write the raw data products in a staging storage area. The system ingests these files into the Science Archive, which is assumed to be co-located with the data processing cluster, in the Science Operations and Data Center. As the data arrives, a process collects the metadata and stores it in a metadata database. The binary files are stored into the permanent science data storage. As the data is saved directly in the format expected for post-processing, it is immediately available for the data-processing pipelines. The Archive Ingestion components follow the architecture defined by the NIST Big Data Reference Architecture (see Section 4.6.19.2).

(b) **CSP Backend Processing**: The Correlator Back End (CBE) receives the CSP data products for sub-band stitching and additional integration and averaging before formatting for transmission to the archive subsystem. The final data products are a function of the observing mode:

- Interferometric visibilities (format TBD),
- 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, therefore, for those observing modes the CBE just has to tag the data products with a unique identifier and write the required metadata fields.

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

(d) **High-level Product Generation:** This function refers to the generation of high-level data products by the post-processing systems, triggered by the availability of new datasets ready to be reduced, or the submission of custom processing jobs. All the observation data and meta-data necessary to generate the high-level data products will be contained in the dataset. This includes pipeline instructions or "recipes" for the supported observing modes. The system will support some of these fields to be overridden, in order to support commissioning, new observing mode testing and other custom processing use cases.

The different types of high-level data products that will be generated depend on the observing modes supported by the system. See [RD10] for a description of the initial observing modes that will be commissioned, including its requirements (classified by their sub-array configuration, correlator mode, and other major and minor attributes). A Standard Observing Mode is one for which all stages of the process, from generating Scheduling Blocks to producing quality-assured science ready data products, is automated, and has been extensively tested and validated for use by PIs. Besides the Standard Observing Modes, the system will support several "share risk" modes with different levels of quality assurance and automation, categorized by their assigned "PI Observing Mode Status Level". The levels are: New Mode Test Observations (NMTO), Shared Risk Observing (SRO), Non-Standard Data Reduction (NSDR), Principal Investigator Data Reduction (PIDR), and Standard Mode Data Reduction (SMDR). Each one of these involve different use case scenarios (including commissioning supporting use cases) and requirements for the offline systems, as described in [RD11].

The structural components and supporting infrastructure (or "fabric") needed to support these use cases will be developed in the context of the NIST Big Data Reference Architecture (a summary can be found in Section 4.6.19.2). An important component of the “Framework Providers” required to generate the high-level data products are the implementation of calibration and synthesis imaging algorithms. This component will be based on CASA (or its successor ngCASA), refactored to support large-scale parallelization, as described in Section 4.6.19.1.

This activity includes the following sub-activities:

- **Offline Calibration**: Calibration activities performed post-correlation by the Offline subsystem. See section 5.2.11 for details.
- **Image/Cube Product Generation**: The imaging process typically runs the CLEAN algorithm. This algorithm executes gridding, de-gridding, FFT and deconvolution operations iteratively in a loop known as the major cycle, with the embedded deconvolution operation being iterative itself, the minor cycle. The gridding operation incorporates corrections for direction-dependent effects such as wide field distortions and the primary beam. Note that when performing self-calibration, both offline calibration and imaging are performed iteratively as part of the same process.
- **Other Product Generation**: Other high-level products, such as catalogs, pulsar data, etc.

(e) **Online Calibration**: As the observation is executed, the Calibration module receives messages from the Metadata Capture module announcing the availability of calibration scans to be processed. The Calibration module reads the corresponding scans and computes calibration tables, which are sent back to the Metadata Capture component to be integrated into the final dataset (or alternatively they are written directly to disk by the Calibration module).

In some cases, the calibration results are loaded into the Online Subsystem components to be applied on the instrumentation. See section 5.2.11 for more details.

5.2.5 Software Functions: Proposal Management and Observation Definition

A decomposition of the Proposal Management and Observation Definition function is shown in Figure 87 and is described below.

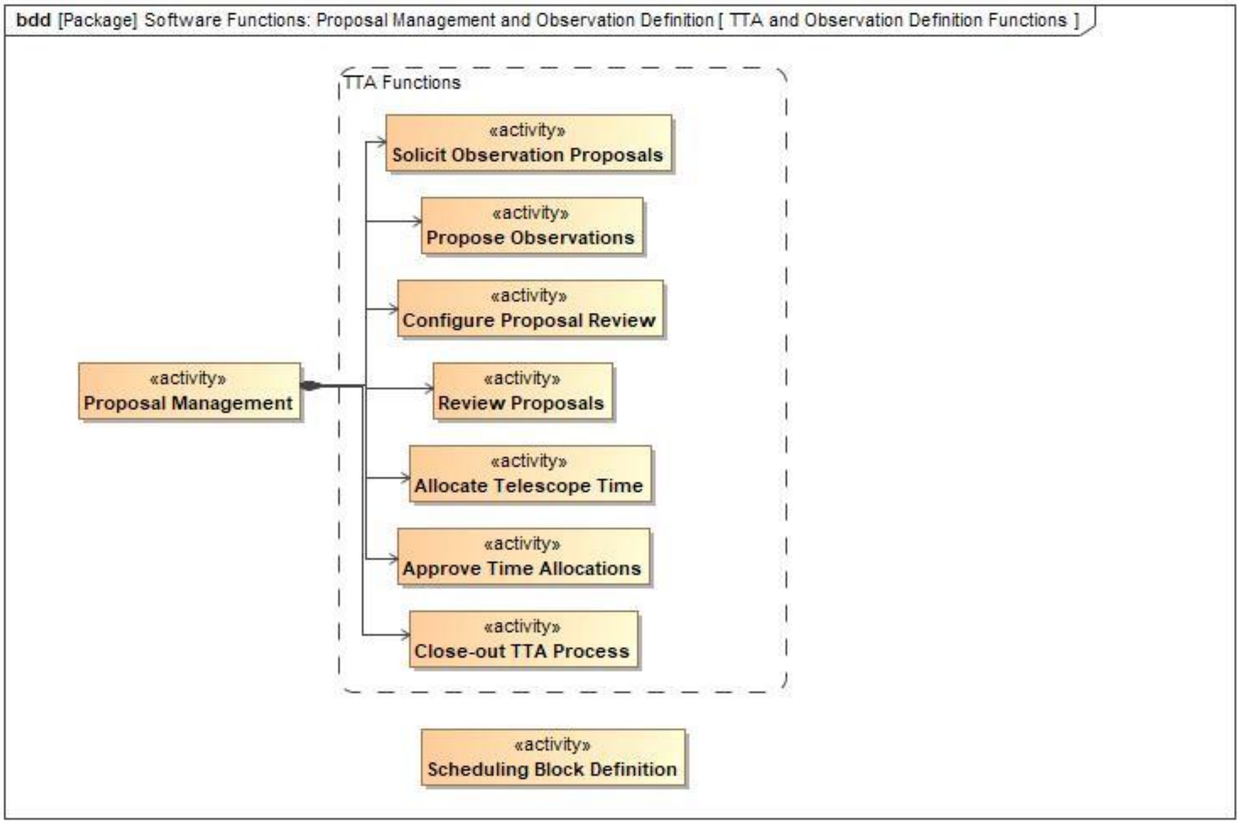

Figure 87: Proposal management and observation definition activities.

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

(b) **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 the approved proposals will execute. The capabilities that will be offered in each Call for Proposals are defined in this activity.

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

(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) **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.

(f) **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.

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

(h) **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.

(i) **Scheduling Block Definition**: This function allows the creation, modification, or deletion of Scheduling Blocks. Scheduling Blocks can be created from the Observation Specification data structures created by the TTA system, or manually. Manual creation of Scheduling Blocks is necessary to support Integration & Verification and Commissioning activities.

5.2.6 Software Functions: Operational Observation User Interfaces

The Operational Observation User Interface functions includes:

(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. This is sometimes referred as QA0. (Regarding observatory quality control functions, QA0 refers to the quality control during the observation; QA1 refers to the quality control of the telescope, including antenna position models, pointing models, etc.; and QA2 refers to quality control functions after post-processing).

(b) **Operator Shift Logging**: This function refers to the annotation of several events that happen during an operation shift. The system provides an application that automatically annotates events such as sub-array creation or destruction, observation beginning and end, etc., and allows the operator to annotate other relevant information.

(c) **Operator Supervisory Monitoring and Control**: This activity refers to the provision of operator consoles for monitoring and controlling the array systems. It is possible that these consoles can be provided by a third-party SCADA system (e.g. Ignition SCADA).

(d) **Scheduling Block Selection**: This function permits selecting one or more Scheduling Blocks for execution in a specific sub-array execution queue. It is allocated entirely in the Schedule module. It provides three operation modes:

- Manual mode: The operator manually selects the Scheduling Block to be executed.
- Advisory mode: The system presents a selection of recommended Scheduling Blocks to be executed, but the operator must manually insert them into the execution queue.
- Fully automatic: The system selects automatically the Scheduling Blocks to be executed.

The first manual mode requires querying the pool of "observable" Scheduling Blocks and presenting the set of attributes that the operator needs to perform a selection. The advisory and fully automatic modes require the current weather data and usually perform a short-term weather prediction to decide the next Scheduling Block to observe.

This activity needs to support Target of Opportunity use cases, which override the normal selection giving priority to specific time-sensitive SBs. The Scheduling Mode may need to interrupt the currently running SBs in these cases.

For VLBI observations, VEX files will be converted into Scheduling Blocks. These Scheduling Blocks must be executed at a precise time along with other observatories, so their handling in the execution queue have special requirements.

(e) **Sub-array Management**: This function refers to the allocation of disjointed sets of antennas in sub-arrays. It is implemented as an interaction of the Array Operator, the Scheduling module, and the Observation module. The Operator decides how the telescope antennas should be partitioned in sub-arrays, and creates sub-arrays by means of a UI in the Scheduling module, which in turn invokes functions in the Observation module for allocating hardware resources to the sub-array and configuring it. An input for the sub-array allocation algorithm is the availability of antenna capabilities. For example, some antennas will have all bands available, but others could have only some in an operational state. Although some of the information can be retrieved directly from the online system status, it may be necessary to retrieve data from the maintenance database to have a complete picture of each antenna's availability. Allocating a set of antennas in a sub-array involves several operations in the electronics sub-elements:

1. The individual antenna frequency offsets need to be controlled for each sub-array. Each antenna LO reference is independently tunable, so this function mostly involves setting the required values at the ATF (for applying the offset) and at the DBE (for correcting the offset) for each scan.
2. Configure the CSP. This involves configuring the DBEs, mapping the DBEs to common array SBPs, and configuring the SBPs.
3. Configure the data transmission between the CSP and CBE, and the CBE resources to process the sub-array data stream from the CSP.

5.2.7 Software Functions: Observatory User Interfaces

The Observatory User Interface functions include the following:

(a) **Data Product Analysis and Visualization**: This activity represents the provision of services and tools to visualize data products. This activity will be elaborated and broken down in specific use cases.

(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.

5.2.8 Software Functions: Control

Figure 88 and Figure 89 show an overview of the software control functions. These functions are described briefly below.

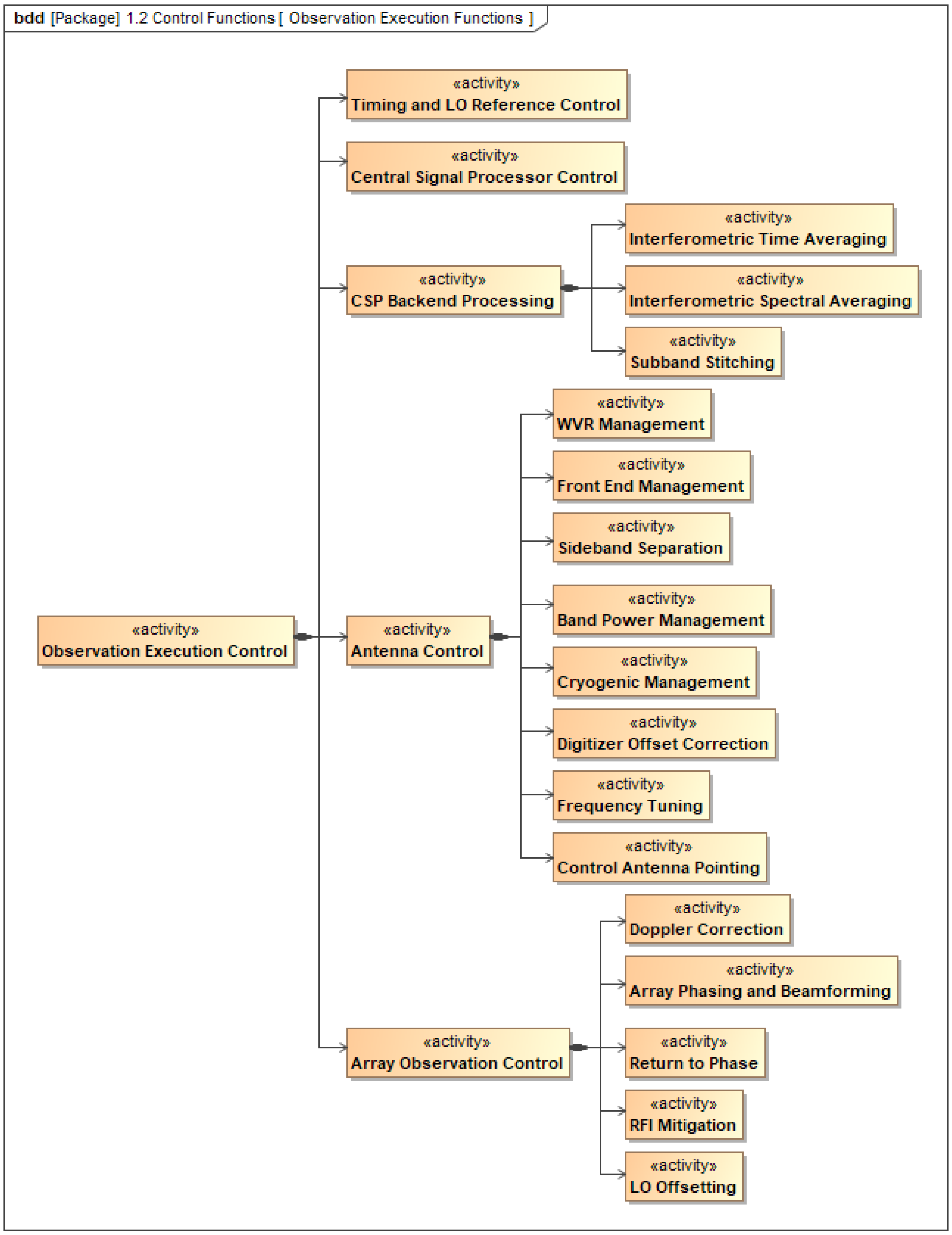

Figure 88: Observation execution control activities.

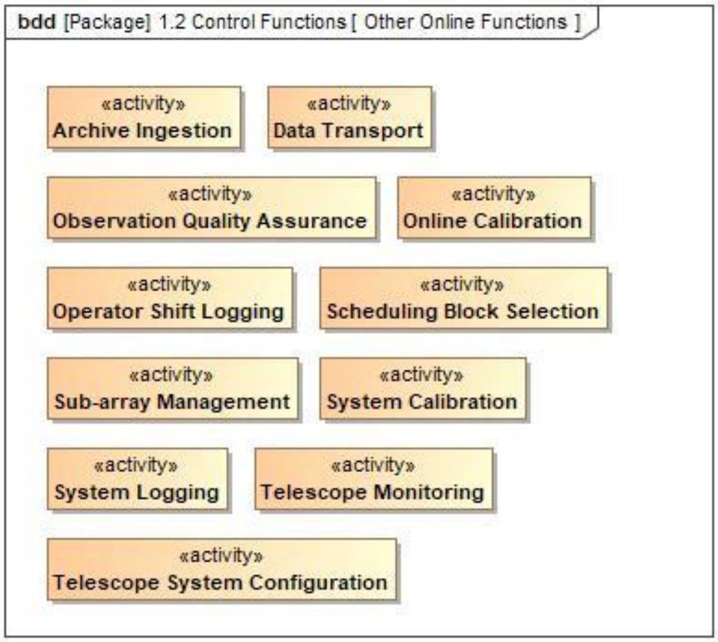

Figure 89: Other online control activities.

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

(b) **Array Observation Control**: Root activity for array control activities. See its sub-activities for details.

(c) **Array Phasing and Beamforming**: Phasing the array means to delay and phase correct the antenna data streams before creating a summed channel (beam) from all antennas. Beamforming means to factor the contribution of each antenna with their own complex coefficients, such that the beam radiation pattern matches a given structure. See Figure 90.

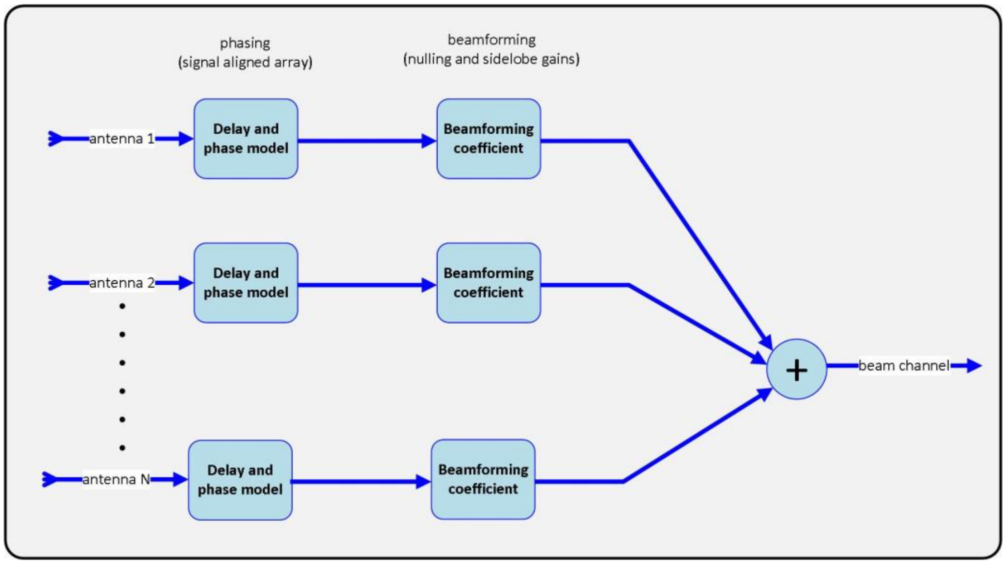

Figure 90: Array phasing and beamforming as two distinct modular functions in the system

Array phasing applies a delay and phase model to produce a coherent beam (or beams) followed by the application of beamforming coefficients before the antennas are summed together. The beamforming process also allows for relative weighting of individual antennas for optimal performance.

(d) **Band Power Management**: This function refers to controlling Front End bands powered up during an observation. By default, all bands will be powered up at all time to maintain stability in the receivers, but the functionality does allow for individual bands to be powered down in case it is needed.

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

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

See Sections 5.2.2.4, 5.2.2.5, 5.2.2.6 and 5.2.2.7 for an overview of the signal path monitor and control points for the CSP.

The CSP is divided in the Digital Back End (DBE), Sub-band Processor (SBP), the Pulsar Engine (PSE) and the CSP Switched Fabric (CSF) that routes data products from each antenna to a corresponding SBP and CSP data products to the Correlator Back End (CBE). The supervisory activity commands the coordinated operation of these sub-elements through the corresponding M&C interface to the CSP. 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 also 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.

(f) **Control Antenna Pointing**: For each scan, the antennas are pointed to a point in the sky. As the antennas have alt-azimuth mounts, their movement is controlled by the Antenna Control Unit (ACU) in horizon coordinates (azimuth and elevation). The sky coordinates, on the other hand, are specified in celestial coordinate systems such as equatorial (right ascension and declination) or galactic coordinates. The supervisor software will perform the necessary transformations and command the ACU. These commands form a data stream when the antennas track a sky position as the Earth rotates. Besides pointing the telescope to fixed positions in the sky, the software should support variable objects or Ephemeris (usually planets and satellites). A list of Ephemeris objects will be supported. The antenna pointing data are included in the observation metadata recorded by the Metadata Capture module. Because this pointing data includes both the commanded coordinates and the coordinates where the antenna was actually pointed (read from the axis encoders), the pointing data needs to be retrieved from the ACU by the Antenna Control Supervisor module—which is local to the ACU—and sent to the Metadata Capture module to be included in metadata tables. This function also includes the control of the feed indexer position – See Section 5.2.2.1 for details.

(g) **Front End Management:** This function is to configure the Front-End receivers for an observation and includes the configuration of the calibration noise diode configuration and bias levels. See section 5.2.2.2

(h) **Cryogenic System Management**: This function refers to the control and monitoring of the Cryogenic system. This function includes the control of the vacuum system and may incorporate a power saving modes based on the variable speed cooling design. This function needs to consider the need for allowing enough time for the cryogenic system to stabilize after coming out of a power saving mode. See Section 5.2.3.1 for an overview of the control and monitoring of the Cryogenic system.

(i) **Digitizer Control and 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.

(j) **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).

(k) **Frequency Selection**: The frequency band and sub-band are configured for each sub-array. This requires configuration of the IRDs and CSP to select the operating frequency band and sub-band.

(l) **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 before formatting and transmission to the archive. The number of spectral channels to average together must be provided as a scheduling block parameter for each scan handled by the CBE. TBC: there might be a need to average at different resolutions based on baseline parameters (e.g. length).

(m) **Interferometric Time Averaging**: The CBE 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).

(n) **LO Offsetting**: To suppress spurious signals and other effects (such as frequency aliasing in the CSP frequency slicing), a distinct offset can be introduced in the frequency reference signal for each antenna individually. The offset frequency reference is used for both the down-conversion LOs and sampling clocks. This offset is applied in each antenna at the ATF and is corrected in the DBE before correlation.

(o) **Observation Execution Control**: This section describes how the system issues control commands to perform astronomical observations. The system must support the following observing modes:

- Continuum interferometry
- Spectral line interferometry
- Total Power (auto-correlation products)
- Pulsar Timing (phased sum mode)
- Pulsar Search (phased sum mode)
- Very Long Baseline Interferometry (phased sum mode)
- On-The-Fly Mosaicking
- Solar Observing

An observing mode is defined as a way of using sub-array resources to meet a specific science objective. Although observation parameters (number of spectral channels, integration time, field of view, etc.) vary, all science use cases fall in one of the above categories.

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 the astronomical objects of scientific interest. The observing mode concept also encompasses the calibration strategies that define the required duration and frequency of the calibration scans.

In practice, observing modes require high modifiability and are typically developed and maintained by scientific staff. Because of this, observing modes are implemented in scripting languages (e.g., Python). The execution of an observation script calls an API that exposes high-level functions of the telescope system. These functions encapsulate the technical complexities of controlling the telescope hardware, incorporating timing and concurrency considerations. The ngVLA system will follow a similar architecture. The scripted observing mode and high-level system API will be implemented in the Observation module. The execution of an observing mode script in the Observation module results in several commands directed to components in the Supervisory layer. These commands include the timestamp of execution, calculated sometime in the future to allow for propagation and processing delays. The supervisory components execute the commands, which in turn results in several operations sent to the Controller boards. The Observation module waits for response messages from the Supervisory components, acknowledging reception of the command, start of the execution, and end of the execution. The Observation module waits for these messages with a timeout, and follows error procedures in case of failures of missing responses. This typically involves sending flagging commands to the Metadata Capture module or aborting the observation in case of critical problems.

Because of the unpredictability of the transmission of commands sent to remote station antennas, several commands will be aggregated in a single message, encompassing a larger time interval. This mode of operation is similar to the execution of VLBI observations, where a script for the entire observation is generated and executed in isolation by each station. Controlling and observation functions can be classified by the scope of involved subsystems. The following sections describe functions specific for Antenna Electronics, Data Transmission, CSP, and correlator Back End systems, and functions encompassing more than one subsystem, i.e. array observation functions.

(p) **Return to Phase**: This function refers to the avoidance of phase jumps when switching frequencies during an observation. All LO mixing operations performed in the signal path must be considered, returning the phase to the value it would have if the frequency had not been changed. The LO reference system is designed to ensure Return to Phase by maintaining independent LO frequency continuity per band. Besides the LO signal transmitted to antennas for down-conversion, it is necessary to control the phase introduced in the digital LO mixing in the correlator. Returning to phase is necessary to jointly calibrate scans observed at different times without bracketing them with additional phase calibration scans.

(q) **RFI Mitigation**: This function is implemented in different stages: at the antenna-based voltage streams; after correlation either in the CSP or the CBE; or after formatting and storage in the post-processing systems. Any RFI excision operation that involves high time resolution visibilities beyond the data rates supported by the interface between the CSP and CBE will need to be implemented in the CSP. This function also requires the development of an RFI monitoring database.

(r) **Sideband Separation Control**: During LO down-conversion mixing in the IRD module, the signal received from the sky is transformed into an IQ pair at baseband, forming a complex signal that is dual sideband. The sideband separation process filters and combines the in-phase and quadrature components such that sideband rejection is maximized and the bandpass equalized. This process happens in the DBE (see section 5.2.2.4). The configuration of the sideband separation coefficients is controlled from the Sideband Separation Control software function. Sub-bands are then generated again as IQ signals which are transmitted from the antennas to the CSP building. The software is required to store the set of sideband separation coefficients in the Telescope Configuration Database. These coefficients are loaded in the DBE at initialization time.

(s) **Sub-band Stitching**: Each spectral window is composed by one or more bandwidth slices processed as a sub-band in the CSP. The CBE must collect the sub-bands in a spectral window and 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.

(t) **Timing and LO Reference Control**: Activities related with controlling the timing synchronization and LO reference devices. This includes the control of the RTG, RTD and ATF subsystems as shown in Sections 5.2.3.3, 5.2.3.4 and 5.2.3.5 respectively.

(u) **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. See section 5.2.3.2.

5.2.9 Software Functions: Monitor

The software monitoring functions include:

(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. See sections 5.2.2 and 5.2.3 for the identification of some of the key monitoring functions of the signal path.

5.2.10 Software Functions: Signal Path Support Functions

The Software Signal Path Support functions include the following:

(a) **Quality Assurance**: Activities related with performing quality assurance over the products archived and generated by the Offline subsystem. (Mention the different levels of QA specified in the Data Processing Concept document.)

(b) **System Calibration**: This function refers to procedures to update system calibration parameters that are expected to be slow-varying and hence don't need to be repeated during each observation.

For example, this includes the calibration of:

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

These measurements involve the execution of specialized procedures and observations. The acquired data will be stored in the Calibration database, along with the time the measurement was performed. See section 5.2.11 for details.

(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. This subsystem function includes both the provision of interfaces to maintain this data and procedures for retrieving and loading the data on the corresponding devices. For hardware devices, this data will be loaded by the Supervisory Layer if the Telescope Configuration database can be accessed. If not, the devices will load default values from internal memory. The system should support updating and loading configuration data with minimal re-initializations. See sections 5.2.2 and 5.2.3 for the identification of some of the key configuration points in the signal path.

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, see [RD03] and [RD09] for additional details.

As specified in requirement CSS13016, 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.

Some 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. A process will be defined for the operator to update these configuration parameters in the Configuration Database and broadcast changes to the devices, keeping these changes under change control.

As pointed out in the Observing Mode Calibration Strategy document, several system calibration observing modes, 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 and other observatory operational procedures.

The flow of data to perform online calibrations can be seen in Figure 50 . The Online Calibration module (a.k.a. TelCal) solves calibration tables, which are then sent to the supervisory modules, where they are translated into hardware parameters and applied into the hardware devices. In several cases the same calibration functions are repeated in an online and offline context, as it is not yet clear how they will be designed into the system. In particular, the beamforming modes could require more online corrections, but details about this are still being defined.

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

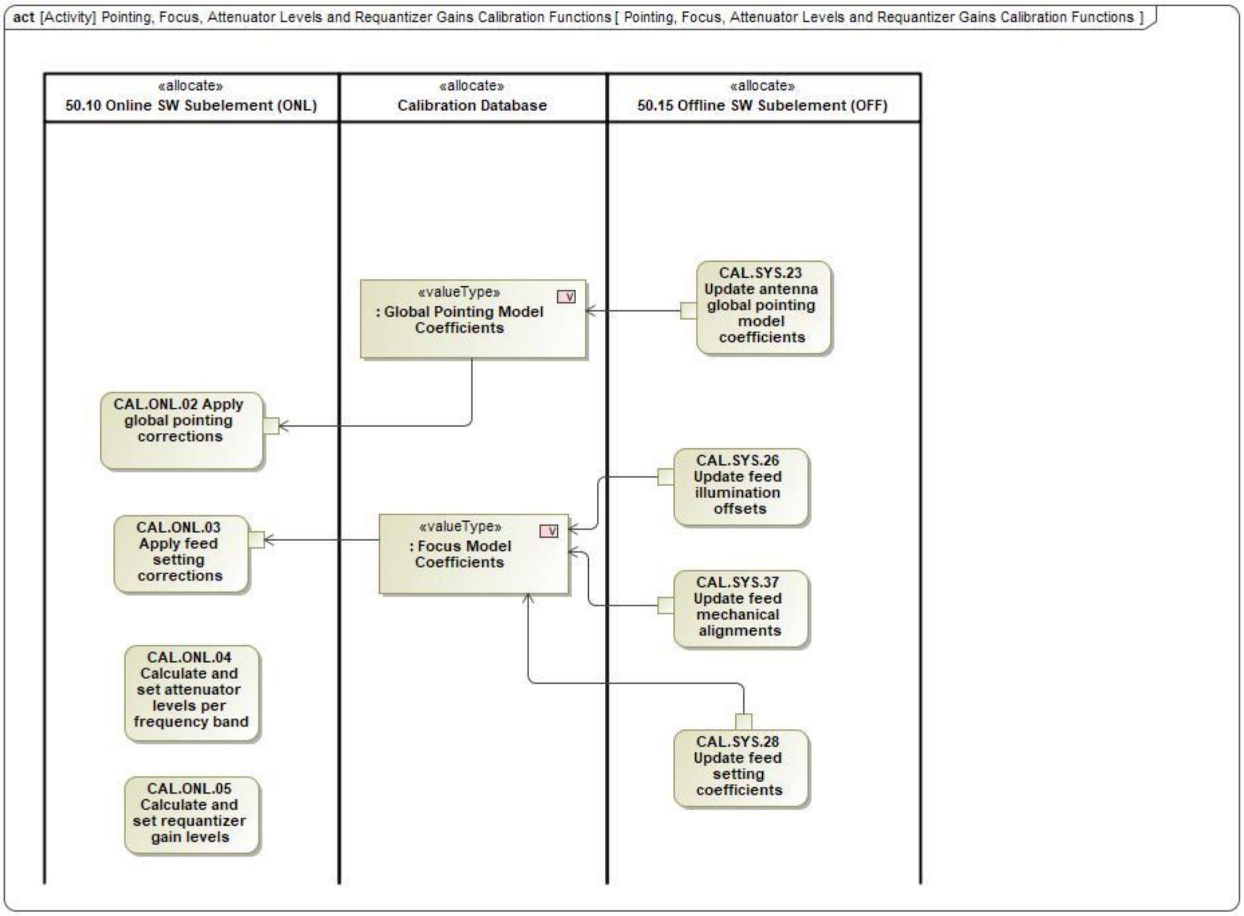

Figure 25: Pointing, focus and attenuator level and requantizer gains calibration activities.

(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 the IRD total power sensor data at the start of each scan. The system checks that the antenna is not pointing near the sun or the Clarke belt.

(d) **CAL.ONL.05 Calculate and set re-quantizer gain levels**: By default, solve the re-quantizer 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 re-quantizer 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 2 Depth of Focus (DOF).

(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

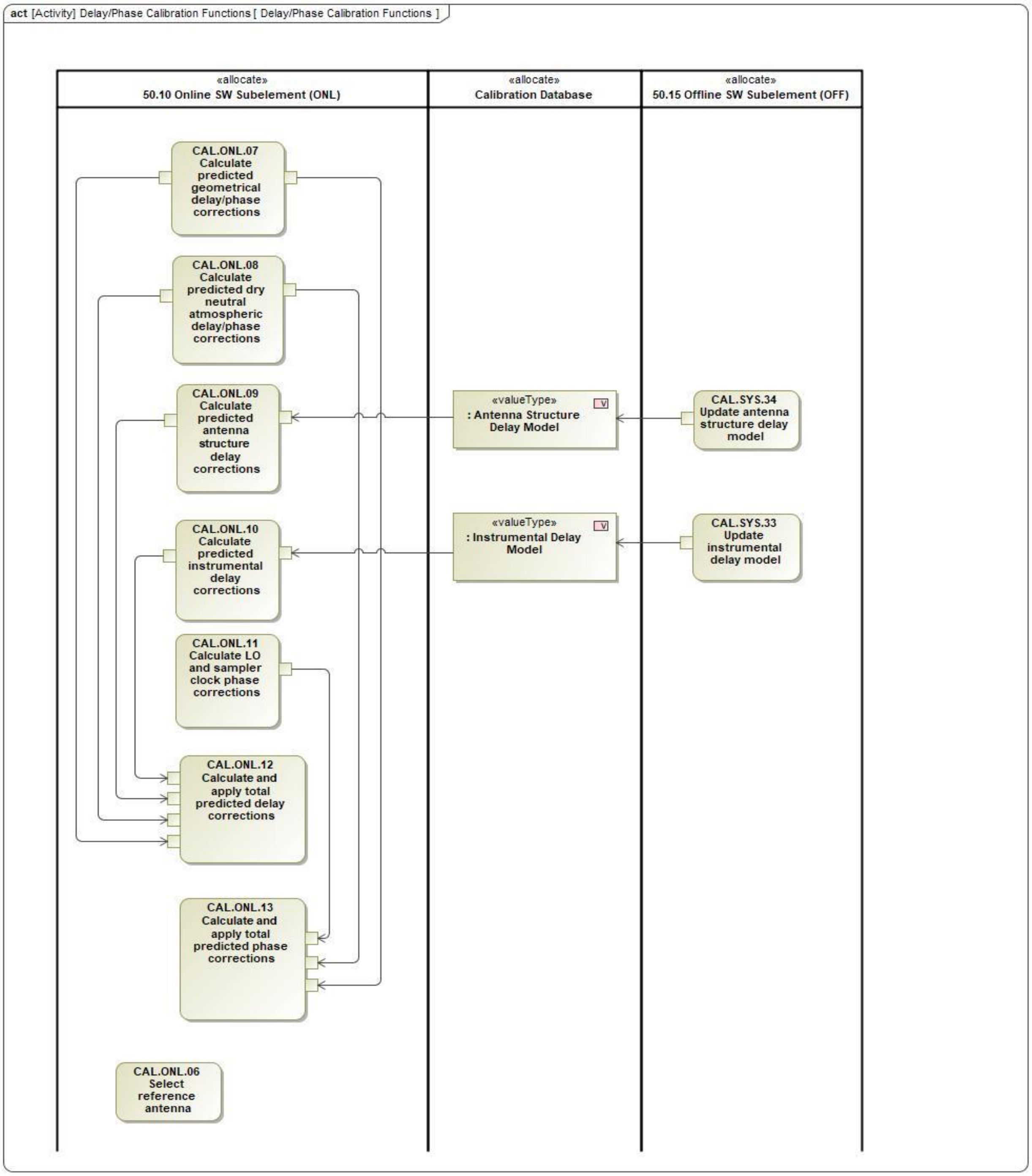

Figure 26: Delay and phase calibration activities.

(a) **CAL.OFF.03 Select reference antenna**: Select the 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, or the IRD total power monitoring data stream. 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 wet 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 axis not perfectly intersecting, and bearings. 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 are 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

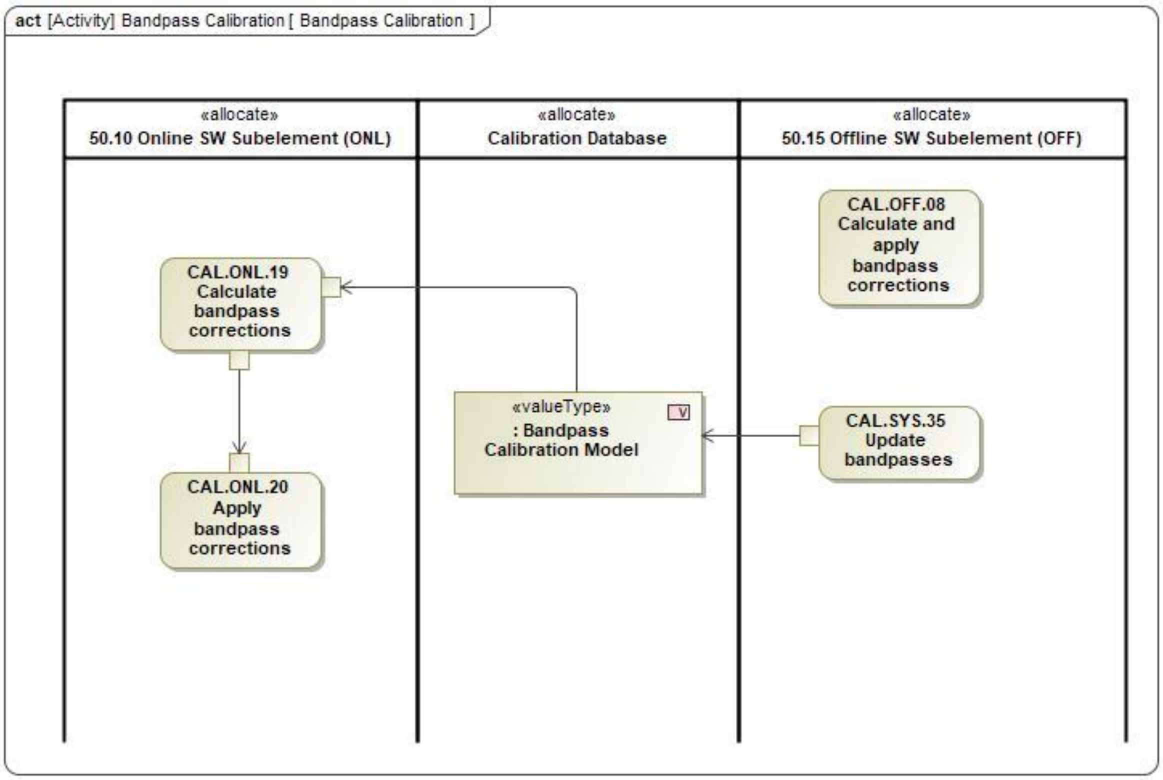

Figure 27: Bandpass calibration activities.

(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**: 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. This will only be performed when a calibrator is observed interferometrically (in-beam or slew) to support a beamforming observation.

(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

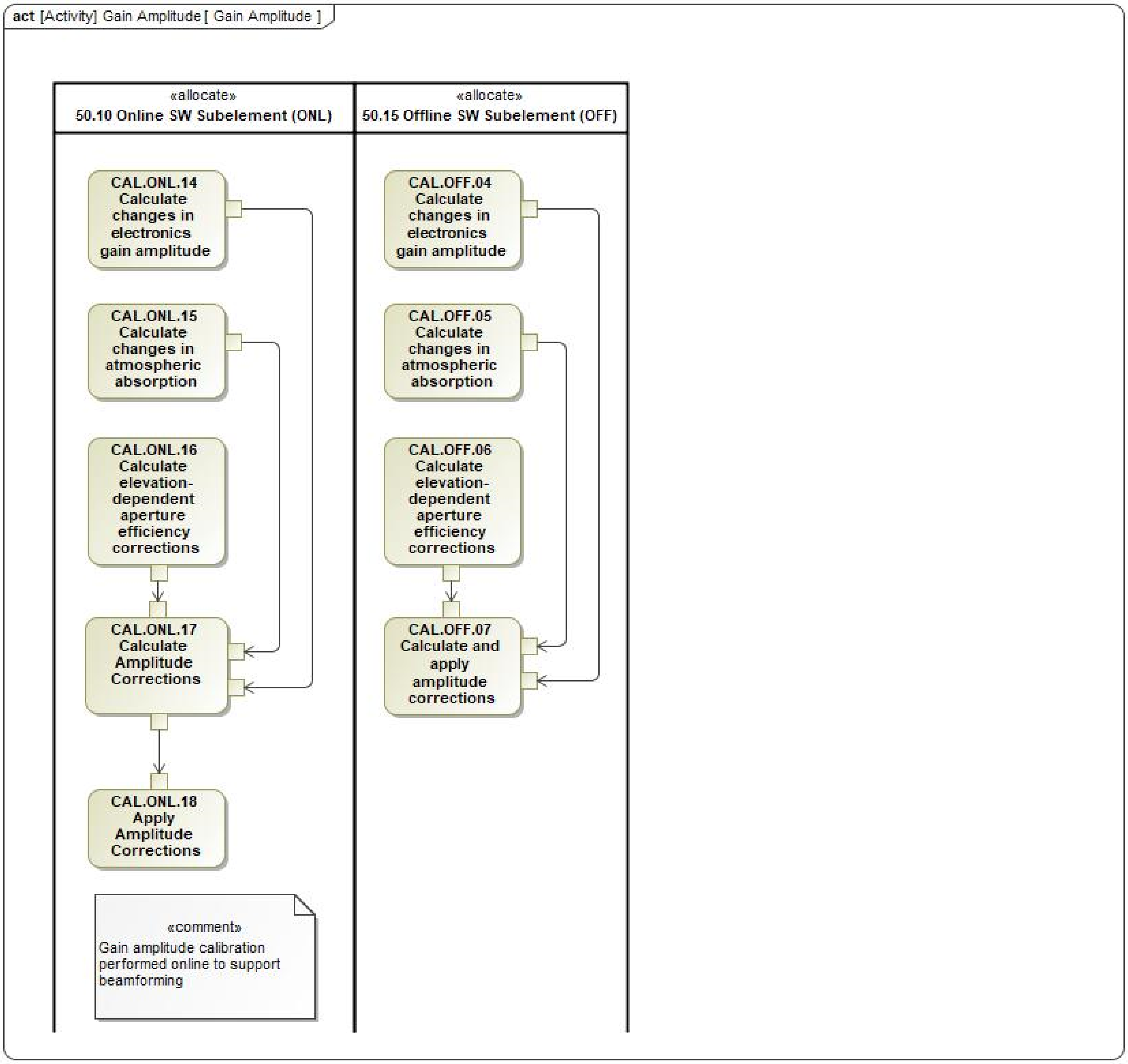

Figure 28: Gain amplitude calibration activities.

(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 amp 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

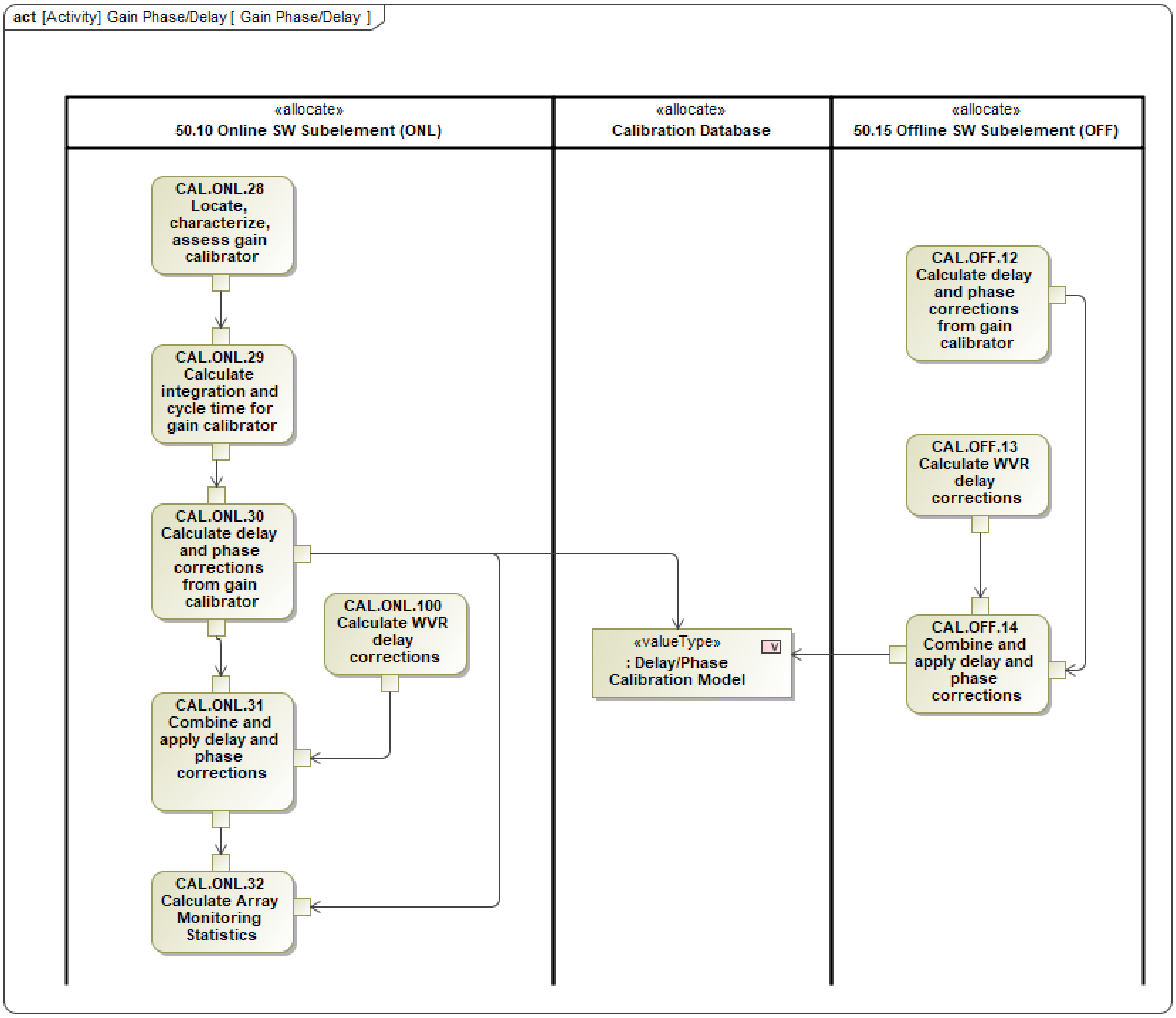

Figure 29: Gain phase and delay calibration activities.

(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 calibration source and target) delay corrections for wet fluctuations. The corrections will likely be a hybrid between absolute and empirical. Given the delay in obtaining the temperature profiles, the observation will probably need to be marked not to be reduced immediately by post-processing, but wait until the temperature profiles are available.

(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).

(d) **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.

(e) **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.

(f) **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.

(g) **CAL.ONL.31 Apply delay and phase corrections from 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.

(h) **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).

(i) **CAL.ONL.100 Calculate WVR delay corrections:** Process the channelized WVR data and associated weather data (e.g. ngVLA weather station surface data). 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.

5.2.11.6 Reference Pointing

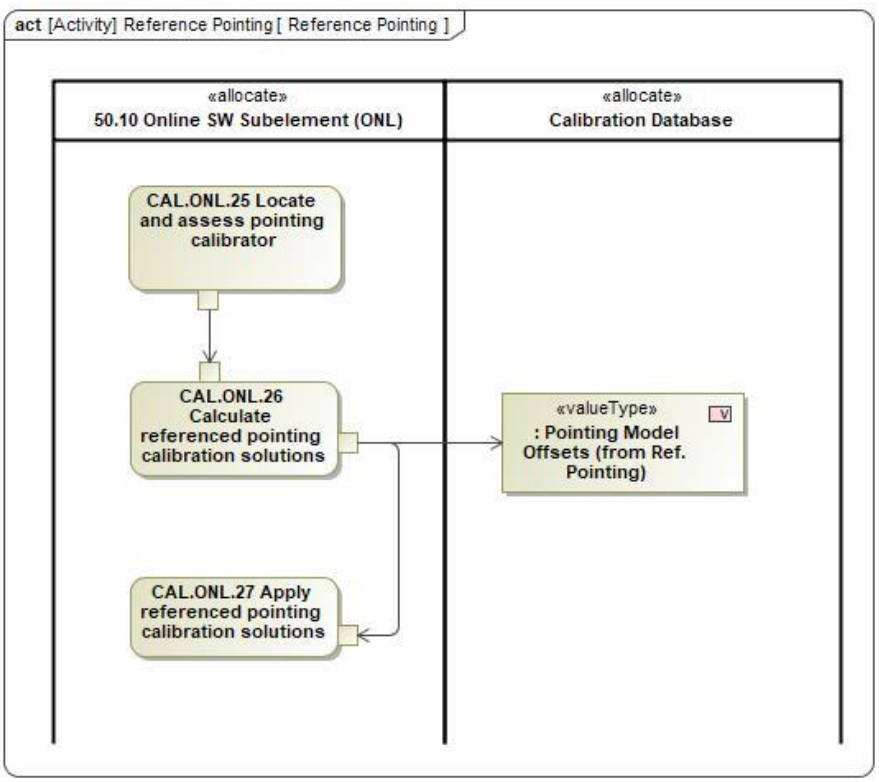

Figure 30: Reference pointing calibration activities.

(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 OK, 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. The advantage of performing this calibration in all bands is that it might increase the archived data level of re-use.

(b) **CAL.ONL.26 Calculate referenced pointing calibration solutions**: TelCal calculates 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. Generate flags for antennas with suspect pointing solutions and repeatability.

5.2.11.7 Polarization Leakage Corrections

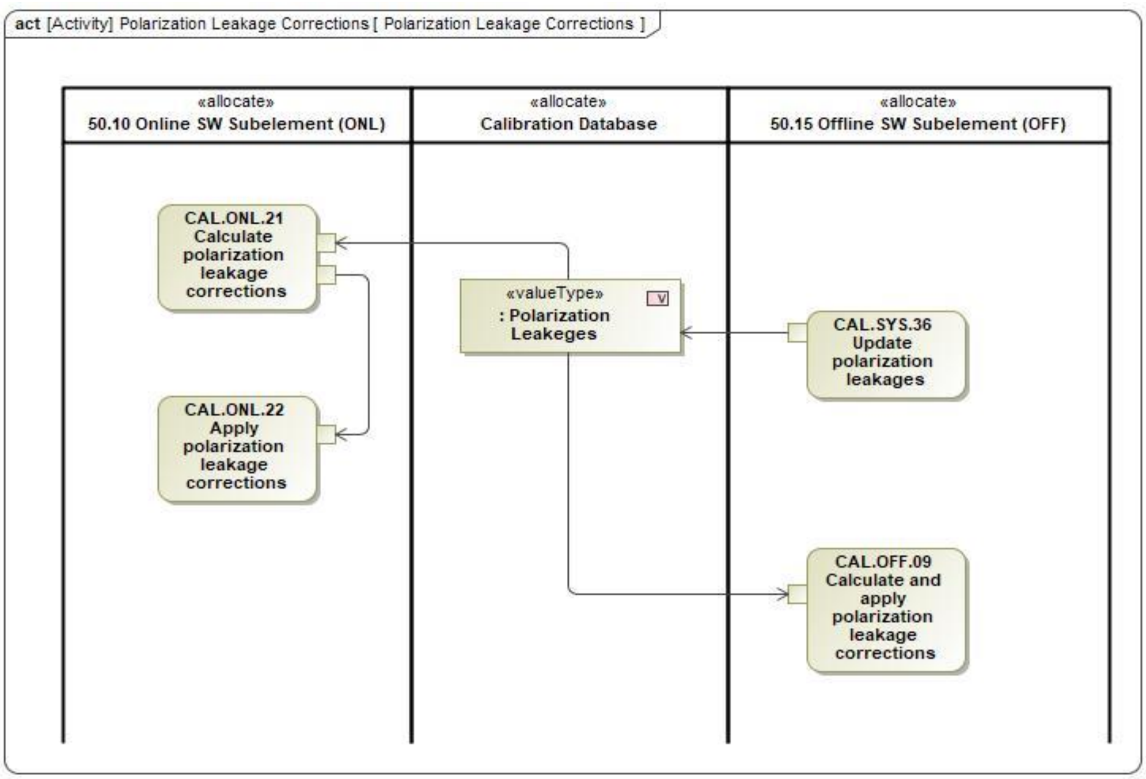

Figure 31: Polarization leakage calibration activities.

(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

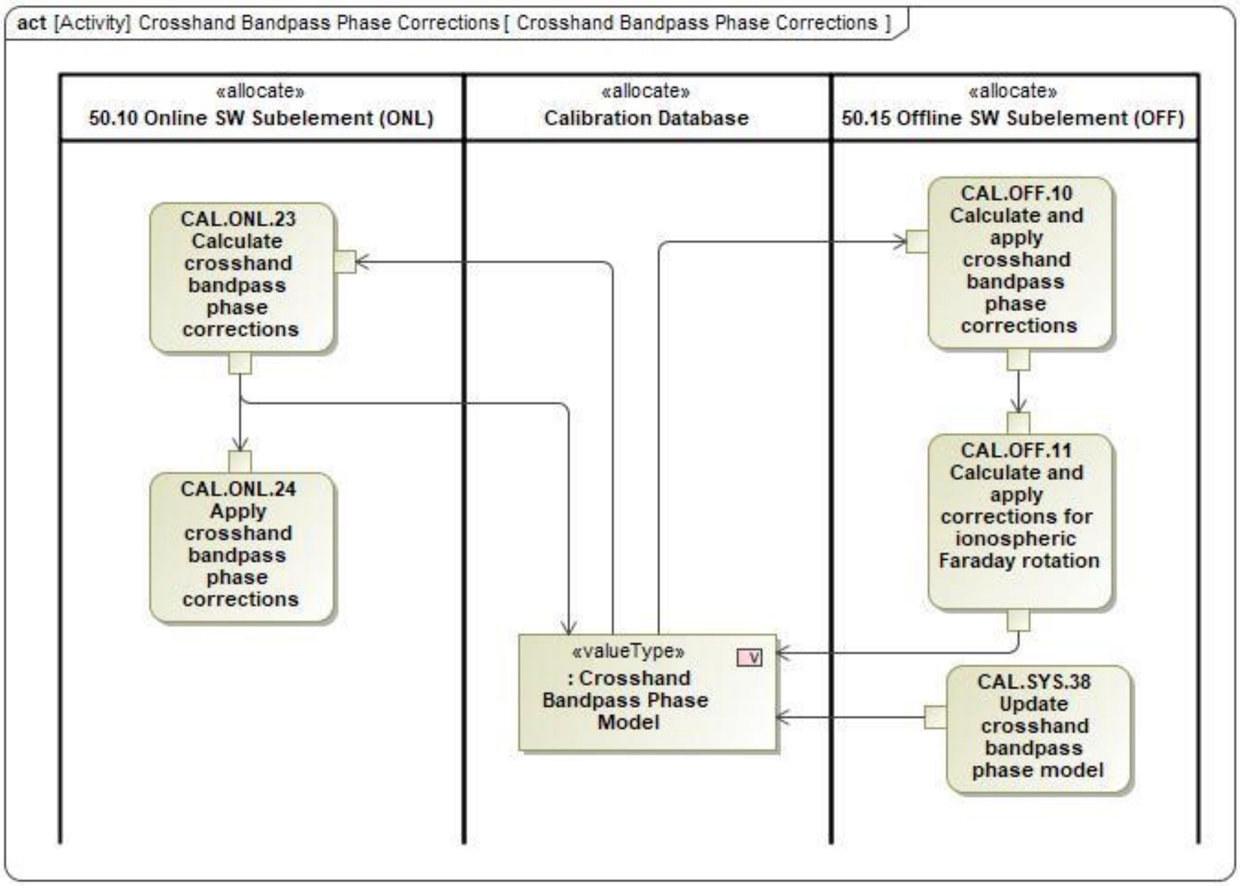

Figure 31: Cross-hand bandpass phase calibration activities.

(a) **CAL.OFF.10 Calculate and apply cross-hand 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 cross-hand data. Given the delay in obtaining the VTEC maps, the observation will probably need to be marked not to be reduced immediately by post-processing, but wait until the VTEC maps are available.

(c) **CAL.ONL.23 Calculate cross-hand 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 cross-hand 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 cross-hand 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 needs 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 in a tower, or satellite, are also possible.

5.2.11.9 Pulsar Binning Calibration

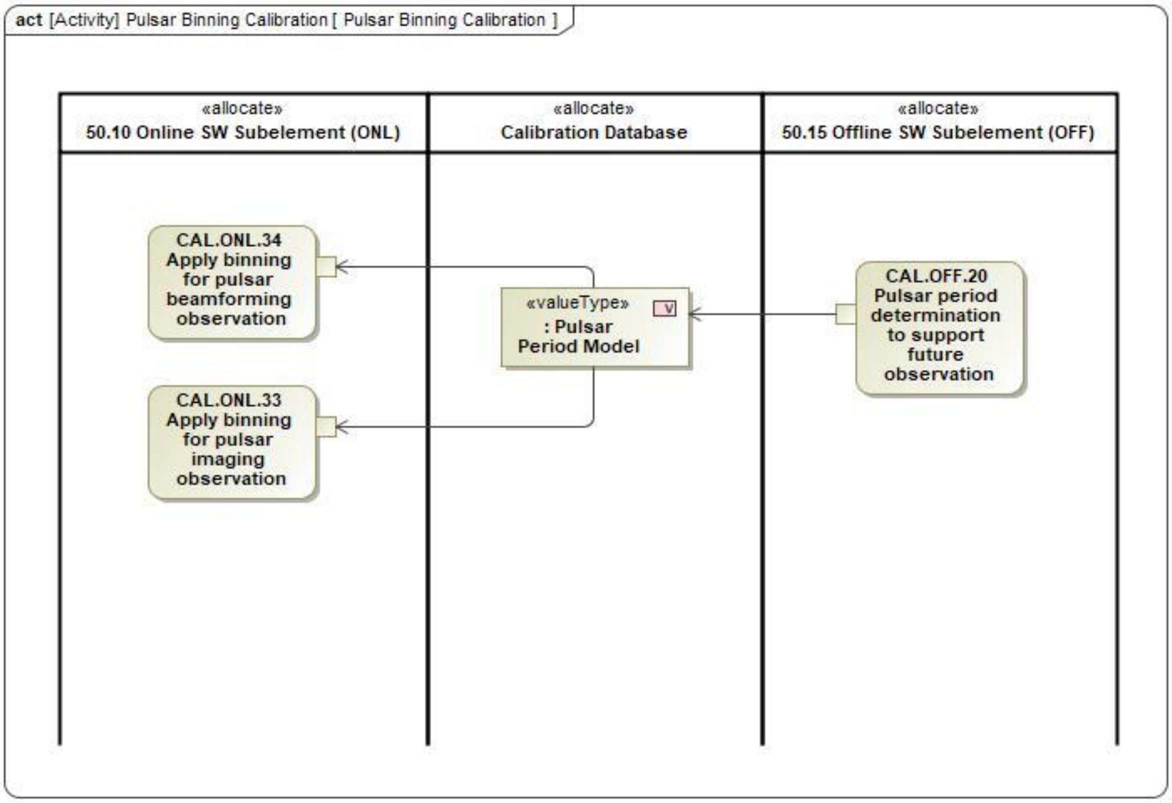

Figure 32: Pulsar binning calibration activities.

(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 Online 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

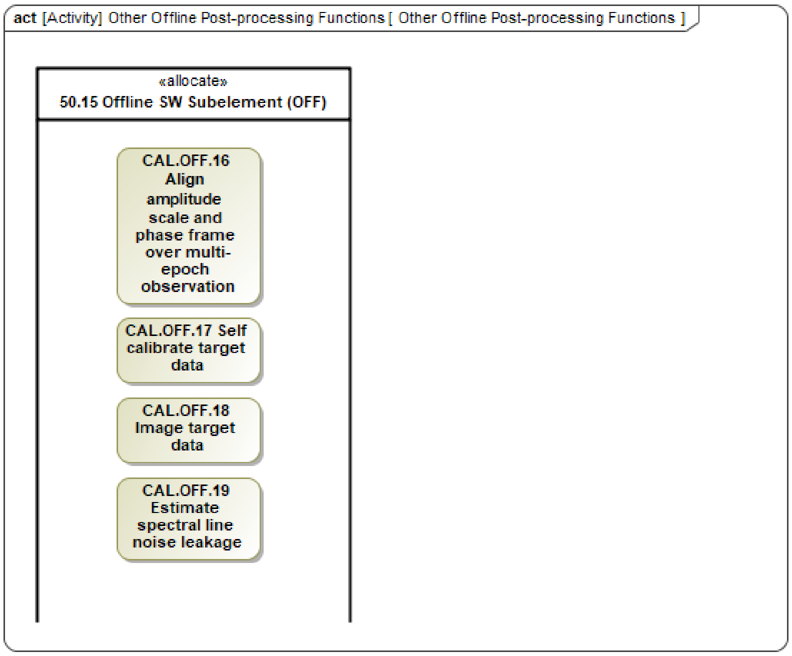

Figure 33: Other offline post-processing activities.

(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 calibration 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**: This function only describes calibration aspects of imaging. See Section 5.2.4 for the main imaging activity. For this process, it will be necessary to pull the antenna primary beam models from the Calibration Database and the antenna pointing 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 System Calibrations

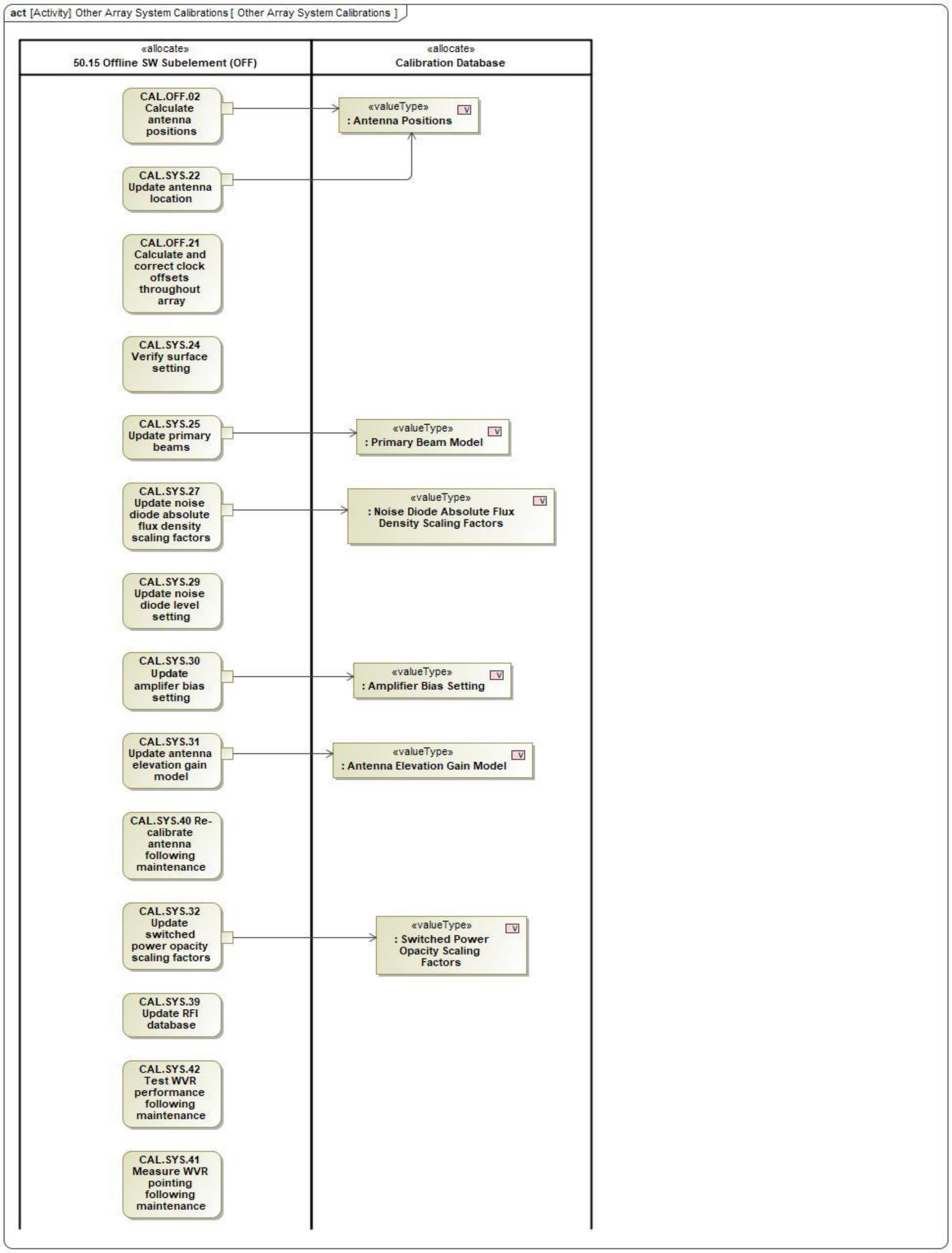

Figure 34: Other array system calibration activities.

(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. This activity calculates the positions at time of observation using the coefficients stored in the Calibration Database. On a related topic, some observations may need to be marked not to be reduced immediately by post-processing, waiting instead until updated coefficients are available.

(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

The Maintenance and Support software functions include the following:

(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 actual problems occur. This function is allocated in the CMMS Integration Module.

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

5.2.13 Software Functions: Development Support Functions

The software functions for Development Support include:

(a) **Commissioning Support**: System functions necessary to support the commissioning activities. This may include the development of special scripts and utilities, which will often require special advance access to (and support for) development branches of online and offline software.

(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
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.

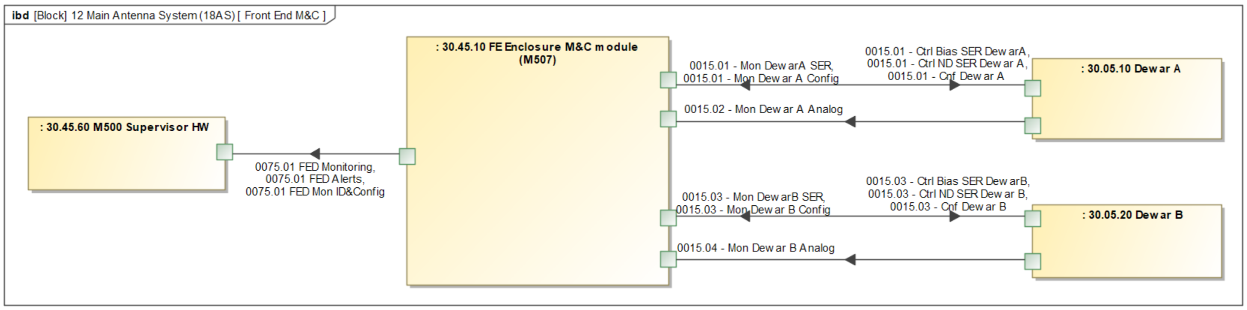

Figure 91: Structural model for Front End M&C

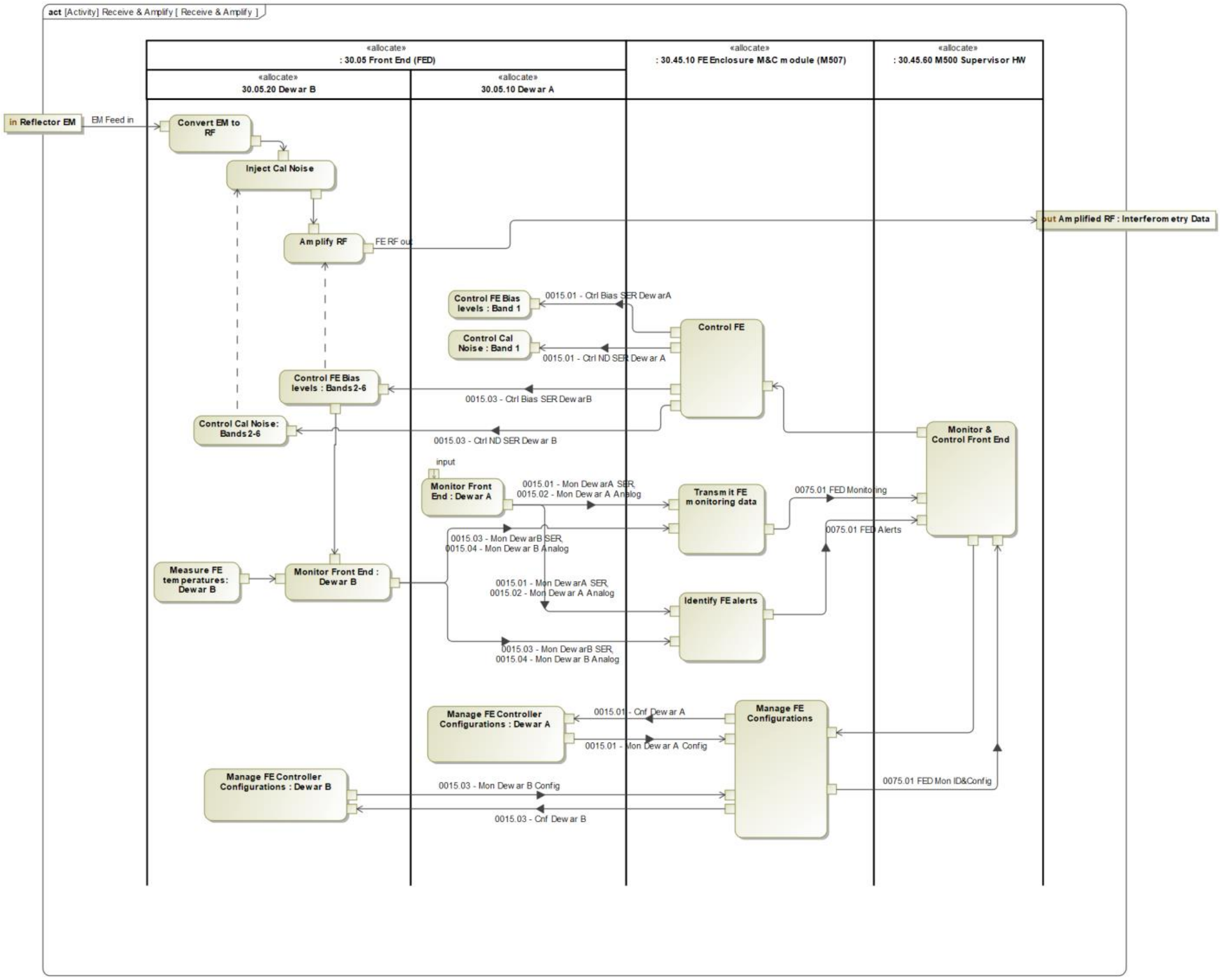

Figure 92: Functional model for Front End M&C

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