Monitoring and Control Concept

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A	2019-07-29	Hiriart, Selina	Monitor and Control Concept Design released for System Reference Design.
A.1	2022-05-19	Hiriart, Brandt, Koski	Draft update for System CDR.
B	2022-06-10	Hiriart, Koski	Updated according to RIDS from internal review. Released version for System CDR.

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1 Introduction

1.1 Purpose of this Document

This document describes general concepts and design choices for the ngVLA Monitor and Control (M&C) System as a preliminary step in deriving its system requirements and specifying its detailed design.

1.2 Scope of Document

The scope of this document is to analyze how ngVLA requirements shape the design of the M&C system, focusing on design aspects that affect the interfaces between the telescope electronic systems and computing. It considers in particular the operational needs for maintenance and troubleshooting. The general architecture of the software and computing systems, including the main data flows involved in performing observations and computing derived data products, are described in [AD01]. The technical requirements for the Computing and Software Subsystem (CSS) can be found in [AD02].

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 Preliminary System Architecture Description	020.10.20.00.00-0002
AD02	ngVLA Computing and Software: Technical Requirements	020.50.00.00.01-0002
AD03	ngVLA System Electronics Specifications	020.10.15.10.00-0008
AD04	System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements	020.10.15.10.00-0002
AD05	ngVLA Stakeholders Requirements	020.10.15.01.00-0001
AD06	ngVLA System Requirements	020.10.15.10.00-0003

2.2 Reference Documents

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

Ref. No.	Document Title	Document Number
RD01	Computing M&C Protocol Trade Study	ngVLA Comp. Memo #2
RD02	ngVLA Maintenance Concept	In preparation.
RD03	ngVLA Cybersecurity Plan	In preparation.
RD04	Enterprise-Control System Integration Part 1: Models and Terminology	ANSI/ISA–95.00.01–2000
RD05	Management of Alarm Systems for the Process Industries	ANSI/ISA–18.2–2009

3 Driving Requirements

3.1 Hardware Driving Requirements

The monitoring and control hardware systems, in the same way as all the antenna electronic devices in ngVLA, are required to comply with the System Electromagnetic Compatibility and Radio Frequency Interference requirements [AD04] and the ngVLA System Electronics Specifications [AD03]. These requirements are especially important for the M&C HIL devices as they will be distributed in several locations in the antenna, in close proximity to other antenna LRUs, and could potentially become important contributors of RFI in the signal path.

In order for spurious signals not to surpass the limits in spectral and continuum Equivalent Isotropic Radiated Power (EIRP) specified in requirement EMC0310 [AD04], the overall goal is -135 dBm/BW ERIP at 10m from the receivers, over the prescribed bandwidth in AD04 has been defined for all M&C Devices. This goal is shown in purple in Figure 1 using simple scaling by bandwidth to first order for comparison sake. This figure also shows the spectral line EIRP limits from [AD04] in blue, which is the most stringent RFI requirement imposed on the ngVLA electronic systems (compared to the *continuum* EIRP limits). Also shown in the figure are the unintentional emission power limit for FCC Class B (residential environments, green line) and the FCC Class A (commercial and industrial environments, red line) for classified commercial devices. As the figure shows, the RFI goal for ngVLA is significantly stricter than the emissions allowed by the FCC. The shielding ratios need to be bandwidth adjusted too. E.g., FCC Class B appears to be over 10 MHz channels, while the ngVLA specs are given at a different (frequency dependent) prescribed spectral resolution. In practice, the narrow bandwidths in the ngVLA spectral line specification make things harder since a spike in emission isn't averaged out over more spectrum.

Figure 1: Basic Spectral Line RFI Requirements

Regarding the hardware requirements imposed by the software expected to run on the M&C devices, the use of the OPC UA protocol implies that the hardware must be capable of supporting an OPC UA server. Possible solutions could be based on a single-board computer running a Linux-based server, with a server implemented in C/C++ (e.g., using the open-source open62541 library, which the project is currently evaluating) or a commercial Programmable Logic Controller (PLC), which commonly include an OPC UA server out of the box. Another alternative is using a software-based PLC such as Codesys, which can be deployed in a number of different platforms, including vanilla Linux systems, and are programmed with the IEC61131 languages. These are relatively simple languages, as the PLC software itself takes care of concerns such as hard real-time task scheduling, fieldbus communication protocol support, and other concerns that require substantial expertise to program. They support extensions written in C when necessary. These systems may be a good alternative to implement the ngVLA HIL software. The project will define the required computing capabilities for these devices after evaluating and prototyping possible software solutions. Defining a specific platform is not necessary for the conceptual stage, but it should be narrowed down for the preliminary design stage.

The system will use Precision Time Protocol (PTP) for time synchronization. This imposes a requirement over the selected hardware platform (the Network Interface Cards or the Ethernet ICs would need to be PTP-enabled).

Besides the requirements outlined above, the M&C electronics for ngVLA need to comply with the maximal electronic specification requirements and to support the maximal device electronic specification requirements, whether they are embedded in a device or connected to a device. The primary purpose of these specifications is to ensure that electronic equipment designed for the ngVLA supports the maintainability and serviceability requirements and have a service life that is proportionate to the planned operating life of the array. These requirements are broken down into a number of categories: safety, basic functionality, autonomous functionality, and maintainability.

3.2 Software Driving Requirements

The main drivers affecting the design of the M&C system are interoperability with industry standards in order to enable the integration of third-party solutions, and the budget constraints on telescope operations (CON002, ngVLA Stakeholder Requirements [AD05]).

Although a detailed analysis of the M&C requirements will need to wait until the hardware device ICDs are completed, the requirements gathered so far suggest a design that doesn't deviate substantially from the control systems that can be found in other domains and industries, which are usually implemented by integrating commercial solutions with a minimum of custom development. This allows the possibility of integrating off-the-shelf industrial control software components where it is possible. An example of this is the current design for the control system of the (MTEX provided) antenna prototype, which will be based on a commercial Programmable Logic Computer (a Beckhoff Twincat system).

These systems have progressed during the last decades in terms of capabilities, interoperability and price, to the point that they may be an attractive alternative for ngVLA, allowing a reduction in development and maintenance costs and the provision of feature-rich systems with a high degree of usability and automatability. This is the intention behind the adoption of the OPC UA protocol and a layered architecture based on ISA-95. Examples of off-the-shelf systems that will be evaluated are PLC software, SCADA systems (e.g., a commercial system like Ignition, or open-source systems like Tango Controls), time-series and stream databases designed for data analytics (e.g. InfluxDB, Apache Kafka), and computerized maintenance management systems. In addition, the current trend of Internet-of-Things (IOT) and Industrial IOT (IIOT) is expanding the ecosystem of potentially applicable solutions for ngVLA. The use of efficient transmission protocols (e.g. MQTT, which is compatible with OPC UA) and edge computing are worth mentioning, as technological enablers of ngVLA's required scalability, given its high number of antennas (and hence monitor points).

The main use case of the IIOT is the collection of data from large number of field devices and the analysis of this data to perform enterprise and maintenance functions such as condition-based predictive maintenance. These analyses can be performed in the cloud or on-premises. Given that it is now possible to deploy field devices with substantial computing power, some of processing can be performed locally, allowing one to reduce the amount of data that needs to be sent over the network and decreasing latencies. This is referred as "edge computing". As other functions related with M&C, this is not specific to the radio astronomy domain, so it should be possible to purchase and integrate a third party system instead of having to develop an in-house solution. Examples of such a system are IBM Maximo and Amazon Web Services IOT.

In order to decrease operational and maintenance costs, the system must achieve a high degree of reliability, maintainability, automatability and usability. Maintenance operations are either preventive or corrective. Preventive maintenance seeks to retain the system in an operational or available state by preventing failures, so it affects reliability directly. Corrective maintenance, on the other hand, includes all the operations necessary to return the system from a failed to an operating or available state. System reliability determines the amount of corrective maintenance activities. Thus, the system should support and facilitate scheduling of optimal preventive maintenance activities to increase reliability and decrease the amount of required corrective maintenance and associated down time. At the same time, making the system easier to automate and more maintainable should decrease both preventive and corrective maintenance costs. The use of a Computerized Maintenance Management System (CMMS) and/or IIOT analytics systems has the potential to significantly reduce these operational costs.

Array operation costs are correlated with the required number of operators. Their activities can be roughly classified as array coordination, observation execution, array supervision, and failure recovery. Costs can be decreased by automating these activities as much as possible and designing a system with a high degree of usability.

The array availability must also be considered. Availability considers both the probability of failures and the time that it takes to recover from them. Given the scale of the ngVLA telescope, there is a relatively high probability of devices failing, compared to currently operating telescopes. The system must be designed to tolerate failures during observations. After recovery, devices and antennas should be reintegrated into the array as efficiently as possible. This can be facilitated by designing the system as a composition of decoupled components that can be operated autonomously with a minimum of centralized interactions.

In general, the ngVLA M&C concept is guided by two complementary principles, derived from lessons learned from the EVLA and ALMA:

- The system should be based on autonomous and decoupled components controlling smart devices,
- The system should be organized and managed as a hierarchically connected system.

The first principle worked well for the EVLA, where the M&C system was structured by Module Interface Boards (MIBs) and MIB-like boards and computers which are highly decoupled, connected to the rest of the system by sending and receiving UDP messages through standard Ethernet interfaces. They were designed as autonomous components. Once they are powered up, they are functionally operative, ready to receive command messages and send monitoring data. In case of failures, a MIB and its controlled electronics can be powered down, recovered or replaced, and powered up again without affecting the rest of the system.

ALMA was structured as a hierarchy of control components, forming a custom Distributed Control System (DCS). This architecture handles complexity well, is scalable, improves reliability, and is well suited for a geographically dispersed system. A DCS allows to distribute the system load on multiple machines and enables the installation of redundancy strategies. It also helps to scale networking loads, as higher level components can receive commands at a higher level of abstraction, which are translated to multiple commands directed to the lower level components. Monitoring can be scaled similarly.

Integral in this architecture is the use of a database to manage the current and past system configurations, tracking which serial number (S/N) identified hardware devices were installed in the system at any given time. Tracking this information is fundamental for the application of automated diagnostics and preventive maintenance algorithms. It is also necessary in order to develop tools that facilitate the task of gathering all the necessary information needed to effectively troubleshoot problems.

4 Architecture

One of the goals of the ngVLA control system is to act as a translator between the observation parameters and the hardware setups required to accomplish the observer's intent. Once the commands to the hardware devices have been issued, the control system monitors the performance of the requested actions and responds accordingly. In general, the supervisory control system is open-loop. Closed control feedback loops do exist inside the hardware layers (e.g. cryogenic control), but at the supervisory level most devices are commanded only at the beginning of each scan. In case of malfunctions, the most common action is to flag the compromised data. Feedback loops that exist at the supervisory level are not related with device control, but involve modifying how the observation proceeds based on real-time information from online calibration results and RFI detection.

Following the principles from the software driving requirements, the control system is broken down into layers, each responsible for converting a higher level parameter into a lower level one. For example: a sky frequency must be translated into receiver tuning parameters; celestial coordinates must be turned into a series of azimuth and elevation commands to drive each antenna pointing; spectral windows are used to inform the correlator configuration, etc. The software hierarchy also follows the logical breakdown of the underlying hardware. At a high level, an array or sub-array is treated as a singular entity, while lower layers in the hierarchy deal with managing correlator resources, individual antennas, or specific hardware within an antenna. An example of these organization is shown in Figure 2. While hardware devices represent physical LRUs and are static, the other levels (Subarray, Antenna, etc.) are software entities instantiated dynamically when a sub-array is created.

This layered architecture allows for the addition of redundancy features to keep observations running as long as possible, even if parts of the system become inaccessible. For example, antennas will have self-management capabilities to continue the observation for a period of time even if the connection to subarray management is temporarily lost.

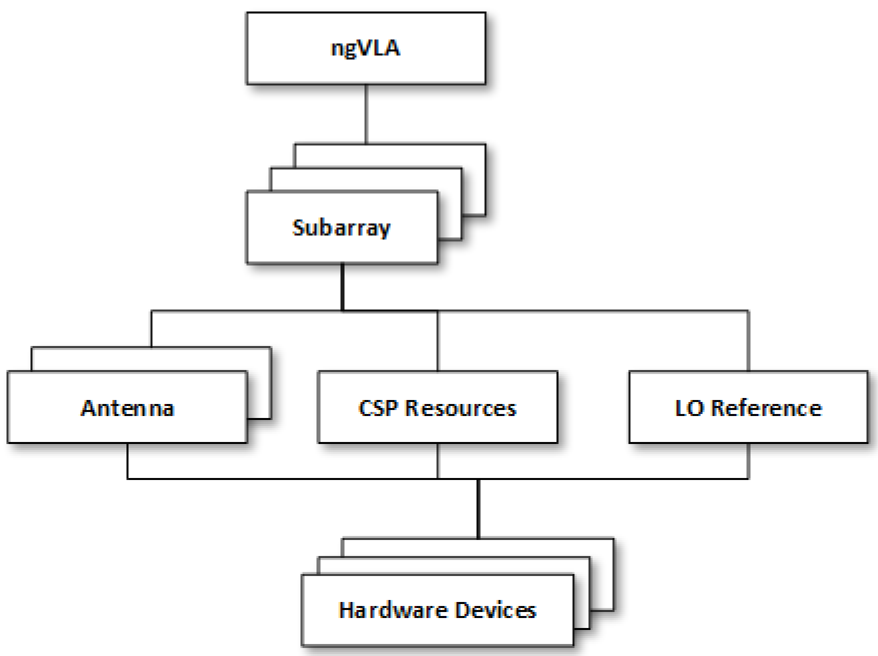

Figure 2: Logical view of the ngVLA antenna control system.

The software architecture is derived from ANSI/ISA-95 [RD04], an international standard for developing interfaces between "enterprise" software (in our case "observatory" software) and industrial control systems. Observatory software includes proposal management/preparation systems, observation scheduling software, quality management interfaces, etc. While the ISA-95 layered architecture has been found adequate to organize the M&C architecture, and maps well with the architectures that can be found in standard industrial control systems and reference models (including the Purdue model for cybersecurity); the standard includes other models that are specific for manufacturing operations. Of these, the most relevant for our case are the ones standardizing the integration of control systems with maintenance management and asset management systems.

For the purposes of describing the ngVLA M&C system, the ISA-95 layers have been re-defined as:

- **Level 0 - Hardware Device Layer**: The hardware elements that are directly involved in the physical processes involved in an astronomical observation.
- **Level 1 – Intelligent Device Layer**: Intelligent devices for sensing and manipulating. Involves the hardware elements that sense, manipulate and convert the signal path. These are HIL boards, the Correlator and other hardware devices. The processes involved in these operations have typical time-frames of less than a second (ms and µs).
- **Level 2 - Supervisory Control and Monitoring**: Control systems for monitoring and supervision. The systems that supervise, monitor and control the physical processes. Includes Distributed Control Systems (DCS), Human-Machine Interfaces (HMI), Supervisory Control and Data Acquisition (SCADA) software. The time-frame is typically seconds to minutes.
- **Level 3 - Observation Operation Layer**: Systems involved in managing the observation workflows to produce the desired science datasets. The typical time-frame is minutes to hours.
- **Level 4 - Observatory Planning and Logistics Layer:** Manages the activities of the observatory operation. 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 lowest layer consists of the hardware itself, for example the antenna drive motors, optical encoders, thermal or vacuum sensors, or frontend electronic components. Communications to hardware are typically done over fieldbus protocols, such as Ethercat, Modbus, Ethernet/IP, but in our case chip-to-chip protocols like SPI and I^2C have been selected, given the proximity of the Level 1 devices (HIL boards for antenna devices) to the controlled hardware and the fact that they will be developed in-house with strict RFI emission requirements. Chip-to-chip protocols are easier to implement and require less digital circuitry on hardware devices.

Level 1 devices are typically PLCs in industrial applications, but have traditionally been custom boards within NRAO (such as the ALMA AMBSIs or EVLA MIBs) (due to RFI requirements, see Section 3.1). The functions allocated to these devices are usually fairly limited (mostly protocol translation), but as the computing power of these type of devices has increased in the last years it may be advantageous for them to perform additional functionality (e.g., high frequency sampling for condition-based maintenance alerts and troubleshooting). Logically they are the last layer of translation, going from OPC UA commands (e.g. tune to a given sky frequency) to hardware commands (e.g. the binary SPI or I^2C commands necessary to tune the LO devices).

Layer 2 includes the Supervisory Control and Data Acquisition (SCADA) system, which includes the remote operator interfaces; and local HMI systems (local displays). Within the logical breakdown, both the antenna management and subarray management systems fall into layer 2. These systems are responsible for collecting monitoring data, and distributing commands to execute the observations.

Layers 3 and 4 represent processes which drive the observation operations, such as observation scheduling, sub-array management, quality assurance, maintenance management, and array performance analysis. These processes are not strictly part of the monitoring and control systems, so they are not described in detail in this document. Layer 3 is described briefly in the next section, given that their components are the primary clients of the M&C interfaces in Layer 2. The Proposal Management System belongs to Layer 4. This and other systems belonging to Layer 4 are not described in this document.

In industrial control systems, devices sometimes communicate directly with one another rather than using the hierarchical system to coordinate between related processes. This mechanism is supported by implementing both an OPC UA server and client in an HIL controller, although it is not currently anticipated that the ngVLA system will have such a requirement. A hierarchical communication path through the supervisory layer is preferred, as the role of the antenna supervisory control is precisely to coordinate operations involving more than one HIL device, and to integrate these with other supervisory functions such as logging and alarm/event management. However, in special cases the delay introduced by hierarchical control could become problematic. No such case has been documented so far, but if a compelling case for direct interaction arises it will be implemented.

4.1 Observation Operations Layer

The operational interfaces will be used by one or more operators and Astronomers on Duty (AoD). These interfaces include observation scheduling, sub-array management, observation execution interfaces, and observation quality assurance interfaces. Note that besides these interfaces, users will have access to supervisory control and monitoring interfaces (e.g. SCADA system), but these are described in the next section.

GUIs for scheduling, observation execution, and quality assurance will be vital for ensuring the efficient operation of the observatory. These will provide scientists and operators with the capabilities needed to realize the observational efficiency goals of the observatory (see requirement STK1402).

All observations, including science, system calibration, commissioning tests and engineering observations, will be performed by the control system as Scheduling Blocks (SB) and executed through the scheduling tool. The SBs specify an observation script (most probably a Python script) that uses a high-level API to control the telescope hardware. For troubleshooting and engineering support, the scheduling tool can also create an interactive or "manual" subarray, reserving telescope resources but allowing the execution of the API commands interactively instead of running the SB script automatically.

4.2 Supervisory Control and Monitoring Layer

The Supervisory Control and Monitoring Layer includes user interfaces for the Astronomer(s) On Duty (AoD) and operator(s), engineering personnel and other members of the technical support staff to allow them to monitor the health of the array, troubleshoot problems, and recover elements in case failures. These interfaces connect with software components that supervise the operations of whole array, individual subarrays and antennas.

The array and subarray components will be deployed in the Central Electronics Building, while the antenna supervisory components will be deployed in the antenna.

The array supervisory components orchestrate the configuration of antenna electronics, correlator resources and the generation of LO reference and timing signals in the context of sub-arrays. It also performs the necessary transformations from high-level commands issued while executing an SB to low-level hardware commands sent to the Intelligent Device layer.

The antenna supervisory components are deployed in the antenna and manage all the antenna electronic devices. This allows for a level of resilience if, for example, an antenna that communicates with the central system over public infrastructure experiences an outage; in such cases the antenna can continue observing for a period of time autonomously. The supervisory control inside of each antenna also reduces the necessary rate of communication to and from the central systems, since the supervisory computer can produce higher-rate commands when needed and buffer and package monitoring data for transmission. It can also implement actions to respond to failures without the delays imposed by longer communication paths. The supervisory control will be essential for long baseline antennas, where the expected delays to/from the central control will be larger and more uncertain.

The SCADA system will provide graphical user interfaces (GUIs) that can display the status of various hardware devices, as well as higher level views of subarrays and antennas. These panels are organized hierarchically, allowing the operator to quickly visualize the status of major elements, but delve into the details of their constitutive elements when required. They allow the operator and AoD to monitor the health of the array, troubleshoot problems, and recover elements in case failures. In general, SCADA operations will be as automated as possible, while still retaining the ability to perform them manually when required. Typically, SCADA systems provide scripting interfaces that can be used to automate operations at this level.

Another useful interface is the "array dashboard", which has been created in ALMA. This draws information from multiple subsystems, such as the maintenance system, weather, emergency alerts, power management, and the control system into a single "holistic" view of the facility.

There are many options available for a SCADA system for ngVLA. Existing open-source systems already used in astronomical observatories include TANGO Controls, EPICS, ALMA ACS, and the EVLA control system. Examples of commercial systems include Ignition SCADA, QuickHMI and Genesis64, to name a few. The project will perform a trade study and prototype the application of different systems and decide on a SCADA solution for the PDR.

The protocol that sits between the supervisory layer and the HIL is OPC UA. The reasons justifying this selection can be found in ngVLA Computing Memo #2 [RD01]. This protocol was chosen because it has become the de-facto standard protocol for supervisory control, enabling interoperability with third-party systems and avoiding vendor lock-in. OPC UA has been purposely designed for industrial automation. It incorporates models for patterns commonly used in control systems such as alarms and events, publish/subscribe communications, configuration parameter management, etc. The standard can be extended to specific industries or domains through their information modeling mechanisms and it has a flexible architecture that allows using it with the most suitable transport-level protocol for the application (e.g., REST, UDP, MQTT, DDS, etc.) and the incorporation of new ones as the industry evolves.

An important function of the Supervisory Layer is processing and presenting alarms & events to the operator, in such a way that the root problems can be quickly identified and recovery actions can be promptly initiated. The relevant standard is ISA-18.2 [RD05], also adopted as IEC 62682. Alarm management will be allocated to the components in Layers 2 and 3. The OPC UA standard allows the definition of alarms and events in the M&C interface, and provide mechanisms supporting the alarm state transitions defined in the standard.

The Supervisory Layer is assumed to either do not have real-time constraints, or have loose deadlines for commands sent to the HIL layer (a.k.a. "soft" real time). It is assumed that real-time constraints are localized to individual devices and will be implemented in the Intelligent Device Layer. An example is the pointing commands to the antenna, which must be applied with high precision timing. In this case, the hard real time deadlines are handled by the Antenna Control Unit. The Supervisory Layer is only required to send a stream of periodic time-tagged azimuth and elevation position updates with enough anticipation for them to be applied at the right time.

In general, the messages sent from the Supervisory Layer to the Intelligent Device Layer can be of two types: time-tagged and "as soon as possible" (ASAP). Time tagged messages are executed with high priority at a specific time, while ASAP messages are executed at the earliest possible time (for example, after any pending time-tagged messages which are queued to execute at the current moment). The pattern for the Supervisory Layer command is to create a schedule of sequential and parallel operations that are time-tagged with times in the future, which are sent to the Intelligent Device Layer with enough time for them to be transmitted, received and applied. The Supervisory Layer then expects to be notified of the status of these operations with appropriate timeouts.

Monitoring data will be generated by the Intelligent Device Layer, then transmitted and processed by the Supervisory and upper layers. For example, a Computerized Maintenance Management System (CMMS), which processes monitoring data to perform condition-based predictive maintenance and optimize the schedule of maintenance operations, is located in the ISA-95 levels 3 or 4. The ngVLA will have thousands of distributed devices generating tens to hundreds of thousands of data points periodically. While the volume of this data pales in comparison to the astronomical data from the telescopes and the correlator, it can still be characterized as "Big Data". The systems that store, transmit, process and support accessing and querying this data need to be designed to comply with the required scalability requirements. One strategy that can be used to achieve these requirements is edge computing. Edge computing is the practice of processing data as close to the point of origin as possible. For example, rather than transmitting high-frequency motor vibration sensor monitor data to a central server to execute condition-based maintenance processing (which could involve, for instance, taking the FFT of the data to detect required maintenance), this processing could be handled locally at each antenna, and only the results sent to the CMMS system.

Other systems that are affected by these scalability requirements are the databases necessary to store the data and support engineering and maintenance interfaces. Databases optimized for monitoring data (usually called Historians in the context of industrial control systems) are another example of the potential integration of a third-party system, as our requirements are not substantially different than other industrial control systems. This is also an area that is benefitting from IOT and IIOT innovation.

In addition, an engineering interface will be provided that allows independent operation of antennas or correlator resources not allocated to an array, as well as privileged access to functions within observing antennas or correlator resources that will not affect data during an observation. If functions which do modify the data are performed, a flag will be applied to the data indicating it may be affected. This engineering interface will provide access to low-level commands which directly controls the hardware. Examples of this design are ALMA's Control Command Language interface and the EVLA MIB console. These privileged interfaces will need to be secured and accessible only to users with the proper authorization level.

More detailed maintenance operations plans are described in the ngVLA Maintenance Concept [RD02].

4.3 Intelligent Device Layer

The Intelligent Device Layer includes the Antenna HIL boards, the Antenna Control Unit, the Correlator and other centralized equipment such as the LO reference and time synchronization equipment.

There are three options for the Antenna HIL boards:

- **Commercial (Industry Devices) - Stand-alone**

  A commercial (or industrial) stand-alone device is a device that can be procured from a commercial source and that needs little or no in-house support logic. It is basically a self-contained device. There are several industrial single-board computers that fall in this category. These devices are usually an FCC Class B, so the amount of shielding required for ngVLA would be 86 dB, in order to achieve the goal of -135 dBm. An FCC Class A device, on the other hand, would require an amount of shielding of 100 dB. Additionally, certain interface features that can emit RFI emissions must be off (Bluetooth, Wi-Fi, HDMI). A commercial device would have to undergo careful rigorous evaluations and the device selected would need to support most if not all of the Electronics Specifications requirements [AD02].

- **Commercial (Industry Devices) and In-House Design**

  A commercial (or industrial) device is one that can be procured from a commercial source, but which requires additional support logic in order to operate. An example could be the Advantech ROM-7510WD-PEA1E, a Single Board Computer (SBC) based upon a TI AM5728 running at 1.5GHz. It utilizes an industrial bus known as QSeven which supports various swappable processors such as ARM, Intel, etc. This processor and others will be evaluated as candidates for the MIB processor core.

  These devices fall usually in the FCC Class B classification, and would have similar shielding requirements as the previous case. The additional in-house support logic would be designed to comply the ngVLA RFI mitigation requirements.

  This type of device includes more interface features than stand-alone devices, which would facilitate meeting ngVLA device requirements. These include serial ports, SPI, I^2C, GPIO, PCI-e, etc. Customized with an in-house design, these devices shall meet and support most if not all ngVLA Electronics Specification requirements.

  The RFI goal using a commercial SoC and in-house carrier concept is to choose an RFI quiet SoC while making sure the I/O on the carrier is appreciably quieter for RFI. For example, if the carrier used I/O fiber links instead of copper links to external devices, RFI emissions would be reduced significantly. While, it may not be as RFI quiet as a full in-house design, even if the commercial SoC board is nominally rated FCC Class B, NRAO would have more design control over the in-house carrier design for RFI mitigation.

- **In-House Design**

  An in-house design is one that is completely designed by NRAO to comply with the stringent ngVLA RFI requirements and the ngVLA Electronics Specifications requirements. An example of these devices is NRAO MIB, a Single Board Computer (SBC) based upon an Infineon TC11IB running at 48/96MHz, designed for the EVLA. It utilizes an in-house bus design that standardized NRAO EVLA hardware device connections. It has been measured to be 20 dB lower than FCC Class B. The amount of shielding required by an EVLA MIB in an ngVLA Antenna is 65dB.

  This alternative gives the ngVLA project the most control and flexibility over the design, in order to meet the ngVLA RFI requirements and Electronics Specification requirements. The design can be used not only on the M&C HIL devices, but for other devices in the antenna electronics as well. The NRAO MIB board is shown in Figure 3.

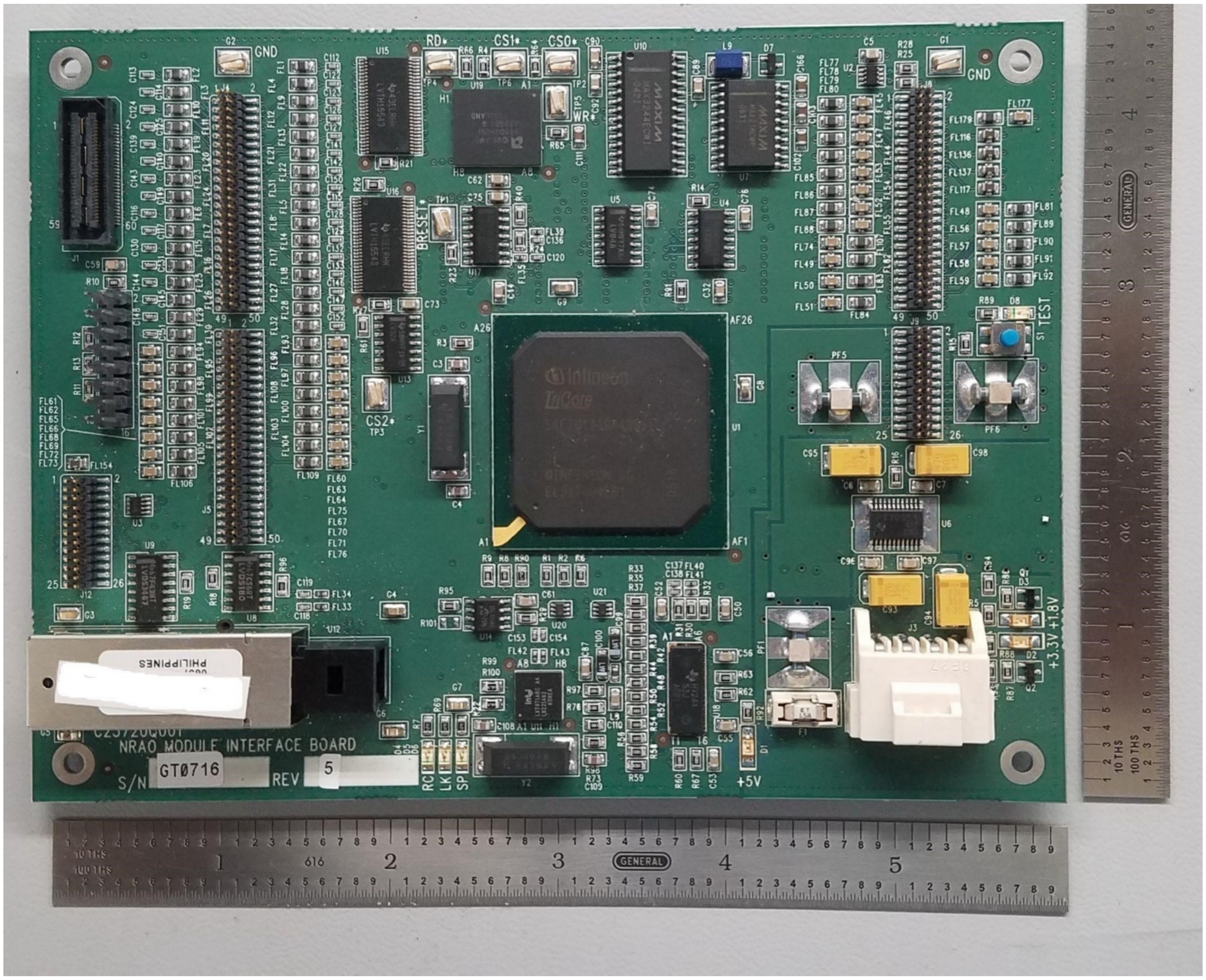

Figure 3: NRAO MIB

The combination of the EMC/RFI requirements and the electronics specifications suggest that the M&C electronics will need to be based on a customized design. The RFI emission limits in particular may be difficult to meet with commercial devices.

The priorities for evaluating these different design approaches are:

1. In-House Design
2. Commercial and In-House Design
3. Commercial – Stand-Alone

These priorities are applicable for all ngVLA Electronics, not only for the HIL devices.

While the lowest performance risk is reached with In-House design, the practicalities of needing a development platform in the near term for the prototype development phase favor pursuing commercial devices with in-house design in the near term. Emission levels can be characterized from such a design and it can be evolved into a full in-house design if proven technically necessary or most cost effective.

4.4 Hardware Device Layer

The hardware device layer consists of line replaceable units (LRUs) which are controlled via interfaces such as I^2C and SPI. This is equivalent to the ISA-95 layer 0, and consists of antenna devices such as antenna drive motors, environmental sensors, and frontend electronics.

The system will automatically discover the serial numbers of each LRU and keep track of their corresponding type and the system slots where they have been installed. This is necessary in order to associate data streams with specific hardware devices. The Supervisor should be able to detect when an LRU has been replaced and reconfigure the device, detecting and propagating the new serial number(s).

Each LRU should be autonomous and come up in an operational state after power up and initialization. The HIL controllers should detect when an LRU has powered up and should execute an initialization routine if necessary. At this point, the HIL should report the existence of the device to the rest of the system through an event and the device should become accessible through the corresponding OPC UA interface. Besides its unique S/N identifier, each LRU has a defined ***type*** that identifies what kind of module it is, and a ***role*** that identifies where it is installed in the system and to which systems it is connected to. As an example, each antenna has several IRD modules, each one installed to receive different polarizations and frequency bands. The event that notifies the system of an initialized LRU should include its serial number(s), type, role and status. This message will be received by the Supervisor, which will configure itself accordingly. The initialization routine should also include a built-in diagnostic, which could also be invoked on demand.

5 Other M&C Functions

This section discusses system functions that are allocated across several layers in the architecture.

5.1 Telescope Configuration Database

Hardware and telescope-specific parameters will be stored in a database which can be accessed when bringing devices up. Each antenna supervisor will cache values when possible for redundancy. These parameters will be associated with hardware devices based on the device serial number, such that even when devices are moved from one antenna to another they can be retained properly. Antenna specific parameters (e.g. pointing model, pad corrections, etc.) will be persistently associated with a given antenna and stored within the configuration database.

The configuration database will also support versioning, so it will be possible to retrieve the history of how the parameters have changed over time.

5.2 Cybersecurity

The ngVLA will utilize physical, electronic, and policy controls to ensure that access to the system is granted only to authorized users. Physical security is beyond the scope of this document, but it is sufficient to note that access to secure servers or sensitive hardware (for example in each antenna) will be guarded with physical security measures to prevent any unauthorized access to the system.

ngVLA will follow the NRAO Cybersecurity Plan (in preparation), which includes policies and security mechanisms to be applied in the monitoring and control system. This document will be included in the PDR. Relevant reference models that are being studied in the context of writing NRAO Cybersecurity Plan are the Purdue model for Industrial Control Systems, ISA-99/IEC-62443 (which was based on the Purdue model) and NIST-800-82 "Industrial Control System Security". Figure 4 shows the Purdue model. The layers are compatible with ISA-95, with the addition of a Demilitarized Zone (DMZ) above the monitor and control system, separating it from the enterprise (or observatory in our case) layers with a firewall.

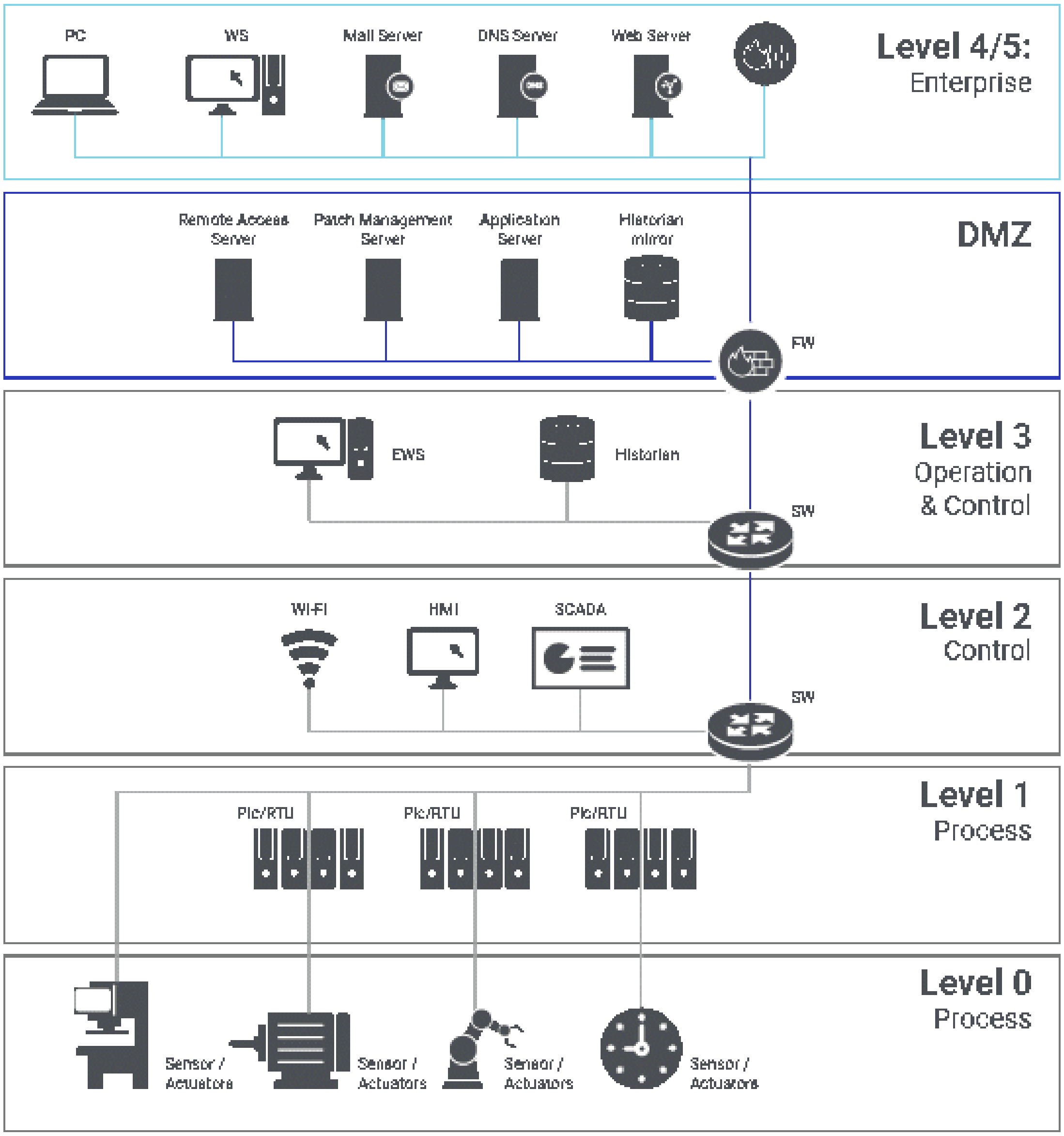

Figure 4: The Purdue model for Industrial Control System security.

Security concerns would normally mean that there would be a private network around the telescope monitor and control system. However, the longest baseline antennas will necessarily use public infrastructure to transmit data and commands. The need to properly secure these antennas is an important requirement for the ngVLA cybersecurity infrastructure.

5.3 Code Generation and Simulation

A primary goal of the ngVLA project is to minimize the amount of maintenance required across all parts of the system. For the monitor and control system, utilizing code generation to create the skeleton of the devices and their hierarchy in the system can save a significant amount of time and effort. ALMA proved this to be an effective technique by generating all monitor and control points code from spreadsheets. For the ngVLA, we would like to take advantage of the project's use of model-driven engineering to generate the OPC UA interfaces (information models and node-sets) directly from the system model. These interfaces can be used to generate C code or be imported into PLC software.

Simulation capabilities will be critical to software testing and verification. A potential option currently being investigated is the use of Functional Mockup Interfaces (FMIs) for simulation of device behavior. FMI is a standard for integrating simulators constructed with different tools (e.g., Matlab Simulink, Wolfram Software System Modeler, OpenModelica, ANSOFT, or hand-written C or Python) in a single multi-domain dynamic simulator. Using FMIs could allow non-software groups to use familiar tools to create accurate models of the hardware that are then used for testing the software control system.

6 Acronyms and Abbreviations

AoD	Astronomer on Duty
API	Application Program Interface
DCS	Distributed Control System
FMI	Functional Mockup Interface
ICD	Interface Control Document
IIOT	Industrial Internet of Things
IOT	Internet of Things
MQTT	Message Queuing Telemetry Transport
ngVLA	Next-Generation Very Large Array
OPC UA	Open Platform Communication Unified Architecture
SB	Scheduling Block
SCADA	Supervisory Control and Data Acquisition
UDP	User Datagram Protocol

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