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# SKA CSP Controls: Technological Challenges

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## ABSTRACT

*The Square Kilometer Array (SKA) project is an international effort to build the world's largest radio telescope, with eventually over a square kilometer of collecting area. For SKA Phase 1, Australia will host the low-frequency instrument with more than 500 stations, each containing around 250 individual antennas, whilst South Africa will host an array of close to 200 dishes. The scale of the SKA represents a huge leap forward in both engineering and research & development towards building and delivering a unique instrument, with the detailed design and preparation now well under way. As one of the largest scientific endeavors in history, the SKA will bring together close to 100 organizations from 20 countries.*

*Every aspect of the design and development of such a large and complex instrument requires state-of-the-art technology and innovative approach. This poster (or paper) addresses some aspects of the SKA monitor and control system, and in particular describes the development and test results of the CSP Local Monitoring and Control prototype.*

*At the SKA workshop held in April 2015, the SKA monitor and control community has chosen TANGO Control System as a framework, for the implementation of the SKA monitor and control. This decision will have a large impact on Monitor and Control development of SKA. As work is on the way to incorporate TANGO Control System in SKA is in progress, we started to develop a prototype for the SKA Central Signal Processor to mitigate the associated risks. In particular we now have developed a uniform class schema proposal for the sub-Element systems of the SKA-CSP.*

**Keywords:** Radio Astronomy, Monitor and Control, Observatory Infrastructures

## 1. INTRODUCTION

The Square Kilometre Array (SKA)<sup>1</sup> will be built over two sites in Australia and Africa. It will be constructed in two phases: (SKA1 and SKA2). When both phases will be completed, it will provide over a million square meters of collecting area through many thousands of connected radio telescopes. The SKA1 phase is in design progress while SKA2 is being planned.

## 2. SKA STRUCTURE

SKA will be built in two sites, one in Western Australia at the Murchison Radio Observatory one in Southern Africa, centred in the Karoo Central Astronomy Advantage Area. Eventually for phase 2 (SKA2) it will be extended to neighboring countries in Southern Africa.

The telescope facilities for SKA1 have been defined as:

- SKA1\_Low, a low-frequency aperture array to be built in Australia; and
- SKA1\_Mid, a mid-frequency array of parabolic reflectors (dishes) to be built in South Africa.

In Illustration 1 there is a schematic representation of the SKA1\_Mid Telescope extracted from the SKA Phase 1 Baseline Design. From the Monitor and control prospective the two facilities will be handled in a similar manner, with differences only in minor details. In the following we will refer to SKA1\_Mid unless otherwise specified.

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The SKA Phase 1 MID Telescope (SKA1\_Mid) is a mixed array of 133 15-m SKA1 dishes and 64 13.5-m diameter dishes from the MeerKAT telescope. The SKA1 dishes will be able to operate up to at least 20 GHz, although initially was equipped to observe only up to 13.8 GHz for SKA1.

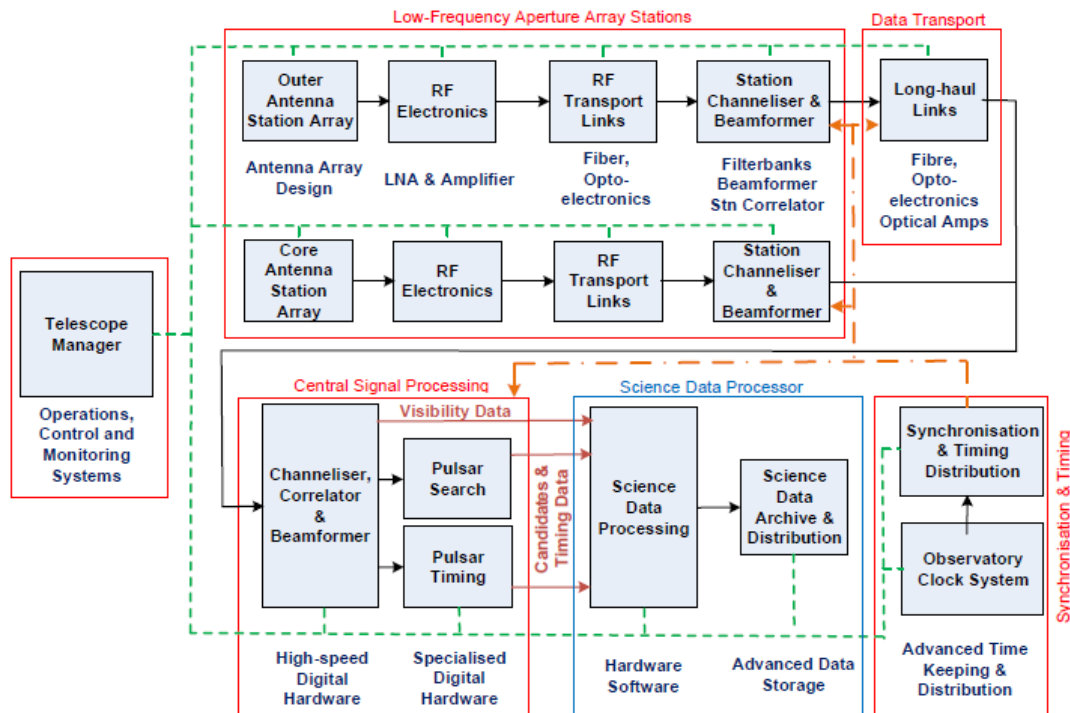


Illustration 1: Schematic representation of the SKA1 Mid Telescope.

Data coming from Antennas, after a fast digitalization and a preliminary process, are fed to the Central Signal Processor (CSP). CSP is in charge to collect, correlate, filter and analyze the observational data, according to the astronomical prescriptions for the current observation(s) coming from the Telescope Manager (TM). Processed data is then forwarded to the Science Data Processor for the final reduction and post-processing in order to obtain scientifically meaningful results. Due to SKA dimension and requirement CSP will be formed by a large set of very fast digital boards and many high-end computing nodes. To meet the requirements imposed by the number of antennas, wide bandwidth and high sensitivity, CSP requires row computing power comparable to the fastest general purpose contemporary computers. To reduce power consumption, most of the signal processing will be performed in FPGAs and GPUs.

To enhance use of telescope resources, each telescope (MID and LOW) allows user to sub-divide collecting area in up to 16 sub-arrays and to operate each sub-array as an independent instrument. Users will be able to schedule observations, select observing mode, start and stop observations for each sub-array independently.

For the sub-array in the “imaging mode” each pair of antennas in a sub-array is cross-correlated to produce full-polarization visibility spectra across the required bandwidth and number of channels. The visibilities are packaged and transmitted to the Science Data Processor (SDP) which produces high-quality continuum and/or spectral-line images.

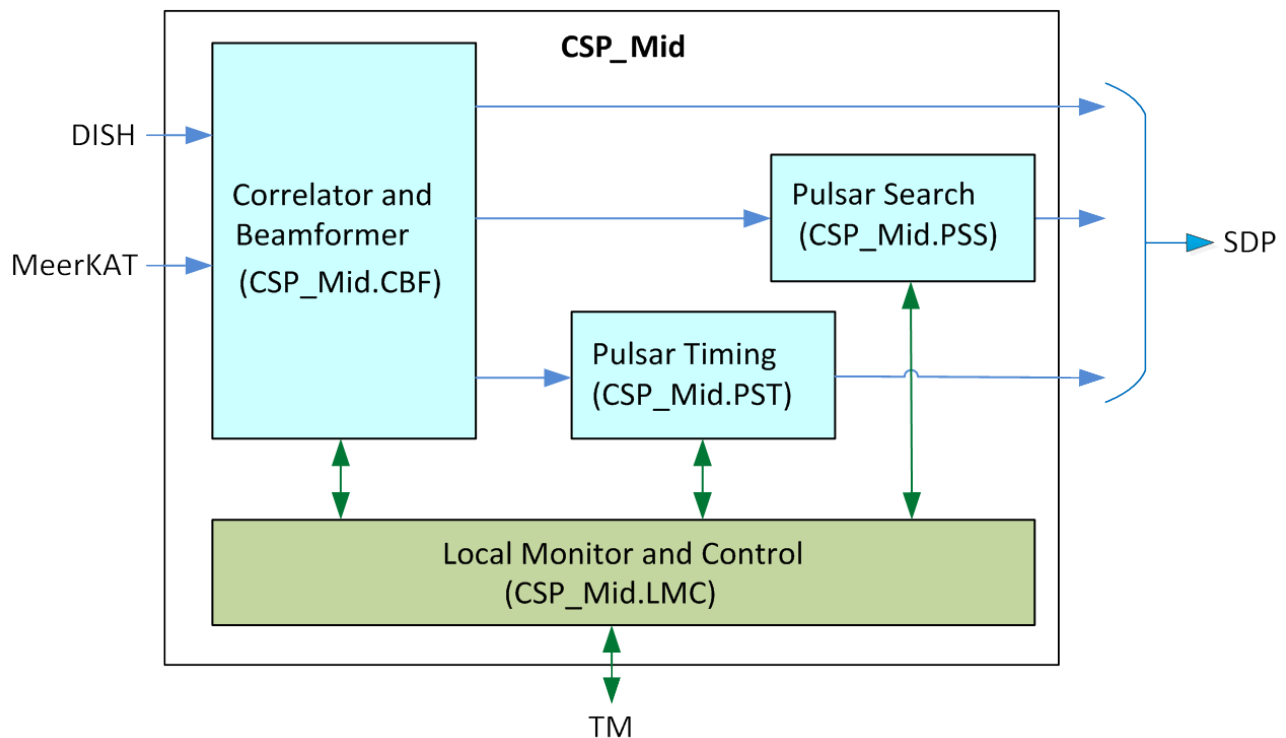
In the “non-imaging mode” a sub-array can form a number of tied-array beams and process data for each beam independently:

- 1) SKA1\_MID is able to form up to 1500 Pulsar Search beams (spread over up to 16 sub-arrays), each covering 300 MHz, based on the sum of selected antennas within +/-10 km of the sub-array center, are used to search for pulsars and

fast transient sources. These data may also be used for relatively crude pulsar timing. Similar functionality is supported by SKA1\_Low for up to 500 beams.

2) Both SKA1\_Mid and SKA1\_Low can form up to 16 Pulsar Timing beams (spread over up to 16 sub-arrays), each covering up full input bandwidth for the observing band, based on the sum of selected antennas within +/-10 km of the sub-array center, are used to very accurately measure deviations between observations of known pulsars and existing ephemerids.

SKA1\_Mid antennas have 5 different bands (700 MHz/pol bandwidth to 2x2.5 GHz/pol bandwidth) with sample word sizes ranging from 8 bits/sample to 4 bits/sample and sample rates ranging from 2.5 to 6 Gsamples/sec. The total data rate from each SKA1 antenna into the CSP is capped at 100 Gbps (CSP needs a single 100GBASE-X4 interface to each SKA1 antenna).



*Illustration 2: CSP Mid structure detailing CSP Sub-elements*

### CSP Structure

As specified in the “SKA CSP Architecture Design Document”, the CSP\_Mid comprises four design sub-elements (see Illustration 2):

1. Correlator and Beamformer (CSP\_Mid.CBF)
2. Pulsar Search (CSP\_Mid.PSS)
3. Pulsar Timing (CSP\_Mid.PST)
4. Local Monitor and Control (CSP\_Mid.LMC).

We will briefly describe each sub-element.

CSP\_Mid.CBF performs two basic functions, correlation and beam-forming. CSP\_Mid.CBF calculates full-polarization cross-correlation spectra with ~64,000 channels for every pair of antennas in each sub-array, including antennas against themselves. Each sub-array may be observing in a different observing band, and spectral zoom may be employed to provide finer spectral resolution over a range of narrower bandwidths. The maximum data rate to the SDP arises when all 197 antennas are used in a single sub-array. In this case, ~64,000 complex spectral channels for each of 4 polarization products are produced on each of  $N(N+1)/2 = 197*198/2 = 19503$  baselines. Each complex product is referred to as a “visibility” and with the minimum specified integration time of 140 msec, 19503 baselines x 4 pol prods/baseline x 64,000 channels/pol prod x 1/0.14 sec  $\approx$  35.6 Giga-visibility/sec. At ~80 bits per visibility<sup>2</sup>, the data rate (to the SDP) is ~2.85 Tbps.

The central beam former, included in CSP\_Mid.CBF, coherently adds signals from all antennas together to form beams, each with the combined sensitivity of the antennas that form the sum, to be used for searching and timing pulsars. In order to adequately fill the primary beam of the antenna, CSP\_Mid is able to form up to 1500 Pulsar Search beams, with 4096 channels per beam. Only 16 Pulsar Timing beams are required, as they are used for targeted observations of known pulsars. However Pulsar Timing requires a much wider bandwidth per beam for sensitivity; for that reason CSP\_Mid is able to form Pulsar Timing beams for up to full input bandwidth for Bands 1 to 4 and for up to 2.5 GHz for Band 5.

The Pulsar Search Engine (CSP\_Mid.PSS) accepts up to 1500 Pulsar Search beams from CSP\_Mid.CBF and searches each beam individually for pulsars and transient sources over a range of dispersion measures (DM), accelerations, and periods. Each processing node operates mostly independently on two of the 1500 beams (TBC) received from CSP\_Mid.PSS at 300 MHz/beam channelized into 4096 channels. The resulting source candidates are sorted and some basic sanity checks are performed before Pulsar Search candidate data is transmitted to the SDP.

The Pulsar Timing Engine (CSP\_Mid.PST) is able to independently and concurrently time up to 16 known pulsars, each in a different Pulsar Timing beam produced by CSP\_Mid.CBF.

The CSP\_Mid Local Monitor and Control (CSP\_Mid.LMC) provides the gateway to the Telescope Manager (TM) on behalf of all CSP\_Mid sub-elements [AD3]. All configuration, control, and monitor messages for CSP\_Mid flow through CSP\_Mid.LMC. The CSP\_Mid sub-elements consist of digital hardware and computers; all sub-elements implement a functionally rich interface that allows for setup of various parameters, operational and observation modes. The Human-Machine Interface (HMI) that allows operations personnel to control and monitor the telescope in order to achieve engineering and scientific goals is provided by Telescope Manager (TM). Interface between TM and CSP\_Mid.LMC is a machine-to-machine interface [AD5], as is the interface between CSP\_Mid.LMC and other CSP\_Mid sub-elements.

CSP.LMC implements an abstract access mode called Capabilities, that represent CSP functionality, in particular receptor-input and PSS, PST and VLBI beams. This allows CSP.LMC to report overall availability and status of the logical functions implemented into CSP, enabling TM and the engineering staff to access the instrument in a less hardware related way and instead to control or monitor a logical function, easing the translation of astronomical directives to hardware-related commands.

### **CSP.LMC role**

The key function of the CSP.LMC<sup>3</sup> is to provide a single point of contact for Telescope Manager (TM), so that TM can configure and execute observations without being aware of the internal CSP design and implementation. CSP.LMC translates parameters provided by TM into CSP.CBF, CSP.PSS and CSP.PST parameters as appropriate. By its nature, CSP.LMC is interface oriented. The interface between TM and CSP.LMC is a machine-to-machine interface, as is the interface between CSP.LMC and other CSP sub-elements.

CSP.LMC co-ordinates functionality of the CSP sub-elements by forwarding information supplied by one sub-element to the other, when required. CSP.LMC reports status on behalf of CSP, including overall CSP state and mode of operation, availability of the CSP functionality and, where applicable, status and progress of the commands issued by TM. Where necessary and applicable, CSP.LMC performs mapping between external view of the CSP and internal implementation. CSP.LMC reports on behalf of the CSP as a whole, and allows TM to monitor and control individual Capabilities, CSP sub-elements, and components, when required.

CSP.LMC makes provision for TM to set CSP engineering parameters, as well as engineering parameters for CSP sub-elements and their components, such as logging levels, alarm thresholds, etc. CSP.LMC makes provision for TM to set mode of operation and initiate state transitions, such as shut-down, start-up, etc.

CSP.LMC implements monitoring functionality such as periodical and on-demand reporting of the health, status and configuration parameters, reporting alerts and significant events.

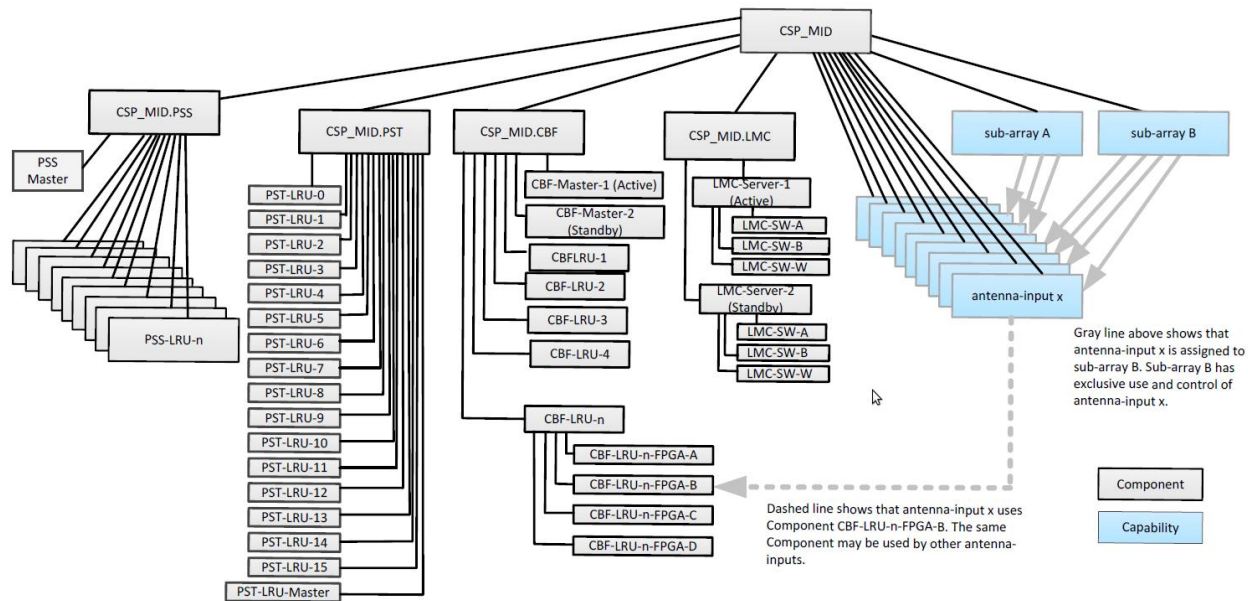


Illustration 3: CSP MID components. Due to the complexity of CSP\_MID, only few subset of all components are represented.

### 3. CSP.LMC BASIC OPERATIONS

The main role of CSP.LMC is to provide a gateway to Telescope Manager, to make provision for TM to monitor and control CSP as a single entity, without being aware of the details of CSP implementation. This section lists some the operational concepts related to CSP monitor and control and CSP.LMC in particular (See Illustration 3).

CSP.LMC is responsible for the overall monitor and control of the CSP including start-up, shut-down, state management, configuration, coordination of the sub-element functionality, upgrades and interfacing to the parent controller (Telescope Manager). CSP.LMC makes provision for Telescope Manager (TM) to monitor and control CSP as a single entity, using a single point of access in each telescope. CSP.LMC provides a level of abstraction to make provision for TM to execute observations without a need to be aware of the details of the CSP implementation. When needed, CSP.LMC makes provision for TM (via the same interface) to obtain status, configure and control individual CSP components. High-level, more abstract, view of the CSP is used during normal operations, to monitor overall status and conduct observations. More detailed views are used for engineering purposes, e.g. for commissioning, testing, troubleshooting, analysis and for experimental (non-standard) observing.

CSP.LMC maintains overall status for the instance of CSP Element and reports on its behalf, so commands/queries addressed to the CSP Element are handled by CSP.LMC. Element level commands and queries may require setup and/or status of more than one CSP sub-element. When an Element level command/query is received, CSP.LMC forwards the command/query to the sub-elements as appropriate, collects responses from all sub-elements and based on those responses generates the response for TM. It is also possible for TM to specify a command Activation Time, which is the time when CSP should begin execution of actions specified in the received message. The activation time can also be specified for commands executed at sub-elements level.

CSP.LMC implements Capabilities that represent CSP functionality, in particular receptor-input and PSS, PST and VLBI beams. This allows CSP.LMC to report overall availability and status of the logical functions implemented by CSP,

enabling TM and the engineering staff to access the instrument in a less hardware related way and instead to control or monitor a *logical function*, easing the translation of astronomical directives to hardware-related commands.

The capabilities functions make also much simpler the concurrent execution of different measurements both in same sky area (using the same antennas subset) and in different sky areas (using different antennas subsets).

CSP.LMC performs all the usual housekeeping required in a complex instrument: maintains connection with the entities higher (TM) and lower (other sub-elements) in monitor and control hierarchy, performs continuous keep-alive monitoring, and executes phased power-up, initialization and shut-down of CSP equipment. The latter is a complex task and must be performed in a carefully planned order to avoid power surges and stress on the power supply at the remote locations.

Of great importance are also two support level tasks: the logging facility and the Alarm system. CSP.LMC maintains the Central Log File in which Alarms and Events are logged in the order in which they were received; each log contains the time when the error/fault/event was reported by the entity that generated Alarm/Event.

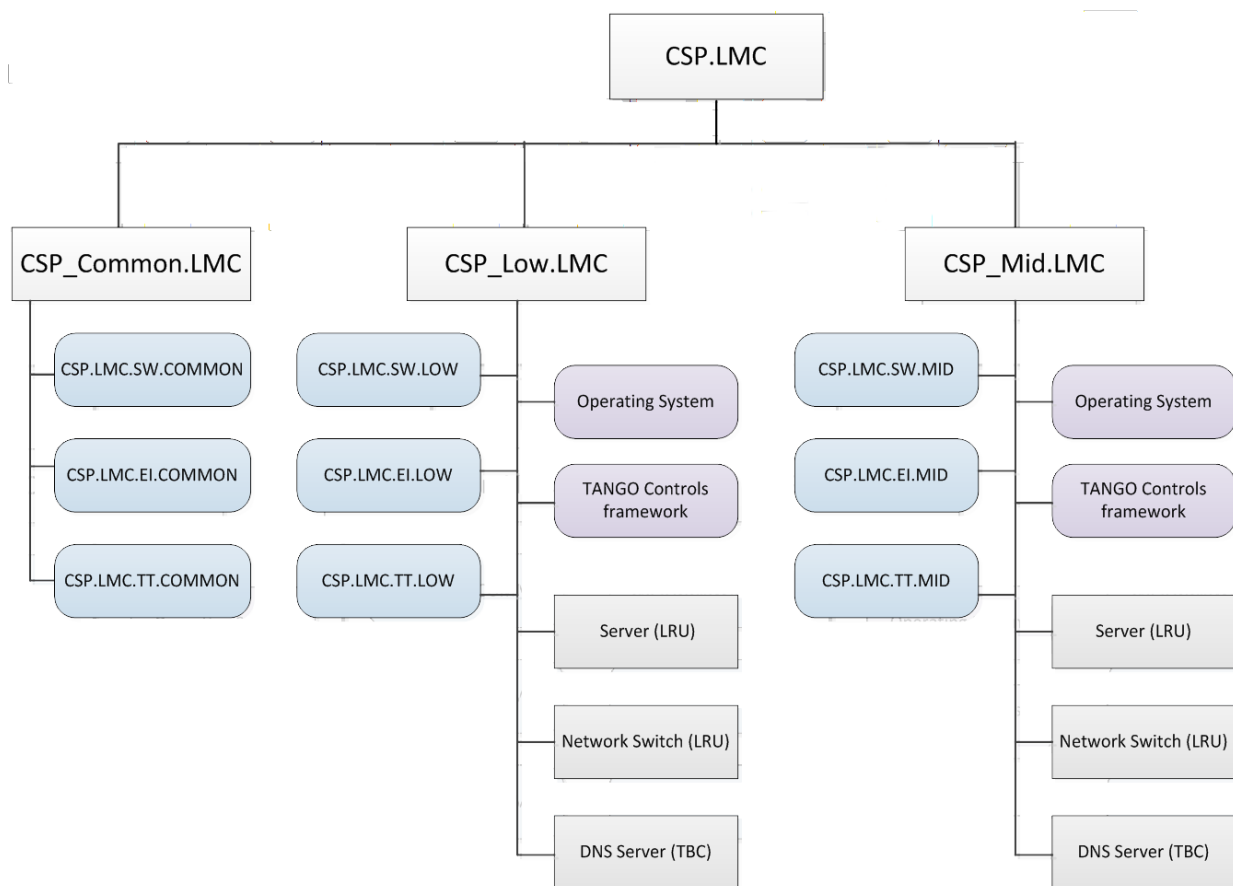


Illustration 4: First and second level components for CSP.LMC\_MID.

#### 4. CSP.LMC IMPLEMENTATION OVERVIEW

CSP.LMC consists of software running on COTS computers. A meeting of representatives of all LMC actors choose in 2015 to have a single software for the global Monitor and Control infrastructure and, as far it will be convenient, also for the lower levels. In the same meeting the Open Source TANGO Controls framework<sup>2</sup> was indicated as the most



promising candidate. For the development of CSP.LMC software Tango Controls is now used as infrastructure up to the possible lower level.

About one year later, a three days workshop<sup>4</sup> aimed to address key areas: provide advanced TANGO best practices and draft a strategy for proficient use of TANGO for SKA. The outcome of this workshop will play a major role on the harmonization process of SKA LMC development.

Following TANGO approach, the CSP element, CSP sub-elements and major components are defined as TANGO devices (see Illustration 4). CSP.LMC implements at least two TANGO devices:

1. CSP - this TANGO device implements interface with TM, reports on behalf of the CSP Element as a whole and handles commands issued at CSP level (for example to power- down entire CSP, including all sub-elements).
2. CSP.LMC – this TANGO device implements CSP.LMC monitor and control and reports on behalf of the CSP.LMC sub-element.

Also sub-arrays and even individual Capabilities will be likely implemented as TANGO devices.

In addition, a top level component CSP\_Common.LMC has been defined as a placeholder for the components common to all CSP.LMC instances. CSP\_Common.LMC comprises the software packages developed by CSP.LMC team that implement functionalities common to all CSP.LMC instances, which are used as a base for the development of telescope-specific software components.

## 5. CONCLUSIONS

The development of a common approach for the development of SKA LMC has been, and will be in the future, long and difficult, due the sheer size of SKA and the required flexibility of operations. The harmonization process of SKA LMC development is still in progress. We believe this effort will have a major positive impact on the global project.

We developed an uniform class schema proposal<sup>5</sup> for the sub-element systems of the SKA-CSP. The results show up from our presented prototype has proven to be fruitful. Under the perspective to participate in TANGO community, SKA since the whole SKA project could contribute to expand the native TANGO features, in a win-win situation.

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