JUMPING JIVE

Project ID: 730884

WP10: VLBI with the SKA

Deliverable:	D10.1 Details on VLBI Interfaces to SKA Consortia
Lead beneficiary:	JIV-ERIC and Square Kilometre Array Phase 1 Project
Submission date:	30/11/2018
Dissemination level:	VLBI Science Working Group members, SKA Organisation Operations Planning Group, SKA Organisation System Engineers, SKA1 Consortia (i.e. CSP, SaDT, SDP and TM Consortia), VLBI Consortium (lead by JIV-ERIC Institute).

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

1 Executive Summary

JUMPING JIVE Work Package 10 “VLBI with SKA” pursues the Globalization of VLBI in the era of the SKA. The inclusion of SKA Phase 1 into the Global VLBI networks (SKA-VLBI) will provide multi-beam capability with µJy sensitivity in N-S baselines with access to the Southern Hemisphere and simultaneous images of the sky at a broad range of spatial resolutions, down to sub-milliarcsecond resolutions for the higher observing frequencies of the SKA.

VLBI is one of the observing modes of the SKA Observatory. The first deliverable of Work Package 10, “Details on VLBI Interfaces to SKA Consortia”, presents a description of the SKA VLBI Element that will provide the buffering and streaming capability to send SKA VLBI data to an external VLBI correlator, as well as all necessary interfaces for scheduling and conducting VLBI observations as part of Global VLBI networks.

The VLBI Element will be provided by an international VLBI Consortium. It will be comprised of a VLBI terminal with VDIF recorders, monitor and control software, and the necessary scripts to carry out the observations. The External Interface Control Document with the SKA1 Observatory describes the VLBI terminal and its interface topology, the specific VDIF format to be used by the SKA1 correlators, the VEX 2.0 file format to generate valid Scheduling Blocks, and the VLBI recorders jive5ab control software to be wrapped in the SKA1 Tango Monitor and Control framework. The individual Interface Control Documents with the SKA1 elements describe the SKA1 MID and LOW VLBI beamforming capability, the routing of VLBI data to the VLBI Terminal and to the external correlator, the monitor and control software, and the required metadata and connections to the Non-Science Data Network for monitor and control purposes.

In close collaboration with the SKA VLBI Science Working Group and the SKA1 Design Consortia, this deliverable has also reviewed the justification, consistency and gaps in VLBI related Level 1 System requirements. Special attention was paid to the SKA1 LOW telescope as its VLBI capability was only very recently introduced into the design. Outcomes from Critical Design Reviews (CDRs) have also informed this study in the form of assumptions on missing L1 requirements. The CDRs conducted thus far have been positive, indicating that the VLBI capability is mature for both the LOW and MID telescopes. Certain technical aspects were clarified and captured in the Interface Control Documents between the different SKA1 elements and the VLBI element and have already been included in the elements designs.

The solution presented in this deliverable best fits the present scenario, but some details may be subject to change, as at the time of writing, the SKA1 Project still needs to complete CDRs

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for a couple of VLBI related elements (Low Frequency Aperture Array and Science Data Processor). Work will continue in the bridging period between the end of CDRs and the start of construction to include any outcomes from these reviews into the final SKA1 System design.

2 Introduction

JUMPING JIVE Work Package 10 “Very Long Baseline Interferometry (VLBI) with SKA” is a preparatory work to *pursue Globalisation of VLBI in the era of SKA*. The main tasks of this work package are:

Task 1: Definition of SKA-VLBI Operational Model, that includes:

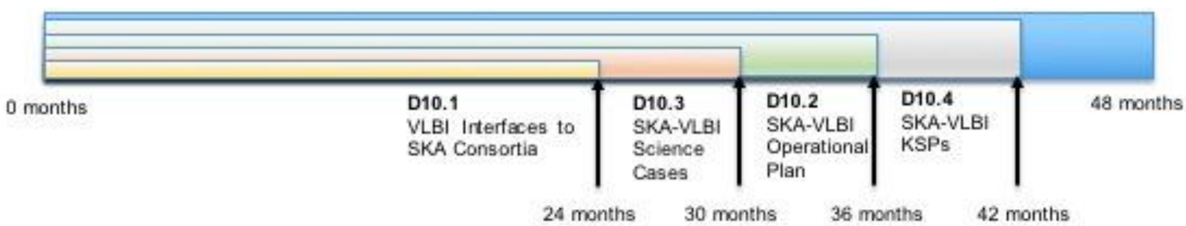
- Ensure adequateness of SKA1 System Level requirements for SKA-VLBI science.
- Definition of VLBI Interfaces with key SKA1 Elements: CSP, TM, SaDT and SDP.
- Verification and Commissioning plan for integration of SKA1 with global VLBI networks.
- Model for proposal handling, time allocation and scheduling, observation management, data delivery and data rights.

Task 2: Development of Global Science Cases, that consist of:

- Include the VLBI capability in SKA Key Science Projects (KSP).
- Revise and update SKA-VLBI science use cases and develop ideas and strategies for Key Science Projects (KSPs), with the support of the SKA VLBI science working group.
- Organisation of SKA-VLBI Science workshops.

The work package WP10 will provide four main deliverables, scheduled in a period of 42 months (Figure 1). Current report presents the outcomes of the first deliverable D10.1, “Details on VLBI Interfaces with SKA Consortia”.

Figure 1. JUMPING JIVE WP10 deliverables schedule



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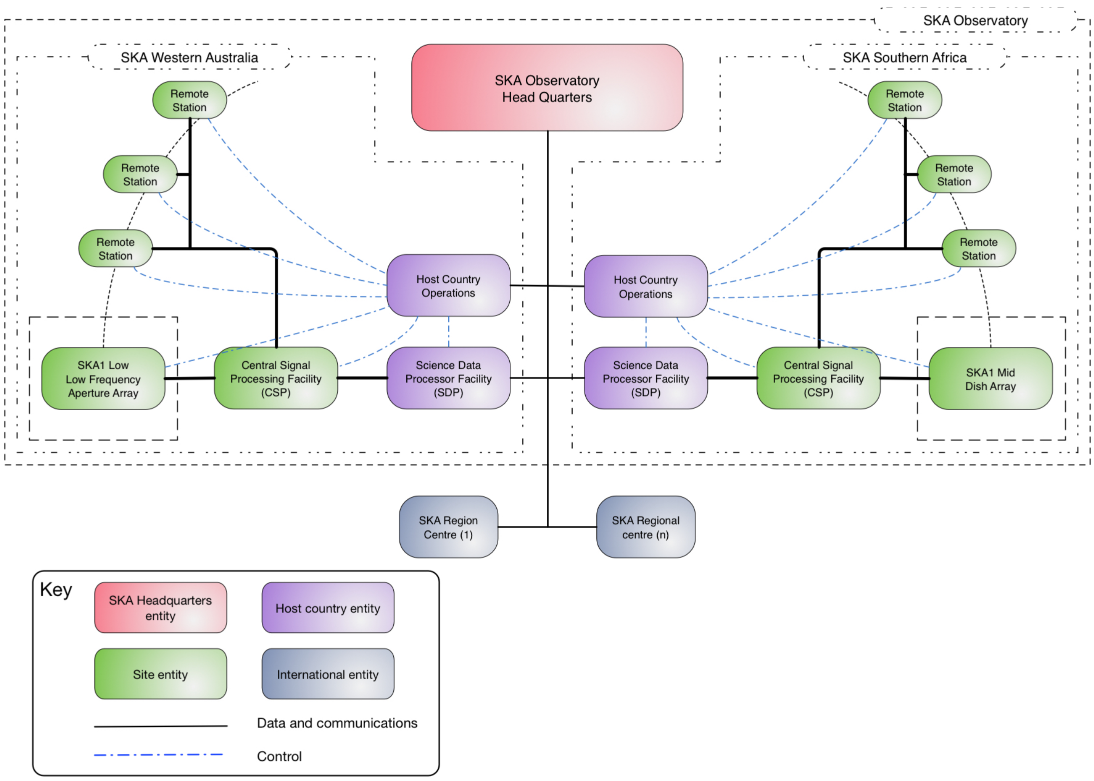
The Square Kilometre Array (SKA) will be the world's largest radio telescope ever constructed. It will be a multi-purpose radio observatory, designed to cover the frequency range from 50 MHz up to 20 GHz, that will play a major role in answering key questions in modern astrophysics and cosmology. The SKA Observatory (Figure 2) will include two very different radio telescopes, one located at the Murchison Radio Astronomy Observatory in Australia (LOW) and the other in the Karoo region in South Africa (MID). The headquarters will be located at the Jodrell Bank Observatory in the United Kingdom. The SKA Observatory its planned to be deployed in two phases.

Figure 2. SKA Observatory schematic



Comparing to existing radio interferometers, the SKA telescopes will access a wide range of angular resolutions (Figure 3) to tackle the scientific problems from many different perspectives. In its initial phase, SKA1 will greatly surpass the capability of currently operational, connected interferometers, with the caveat of lacking very high angular resolutions. Nowadays the highest angular resolutions are achieved by Global VLBI observations, which use coordinated networks of radio telescopes located around the globe and in space, to synthesize an equivalent Earth size instrument or even larger. Inclusion of SKA1 with the Global VLBI networks (SKA-VLBI) will provide access to very high resolution to SKA science programmes in anticipation of the science to be realized with the full telescope deployment (SKA2).

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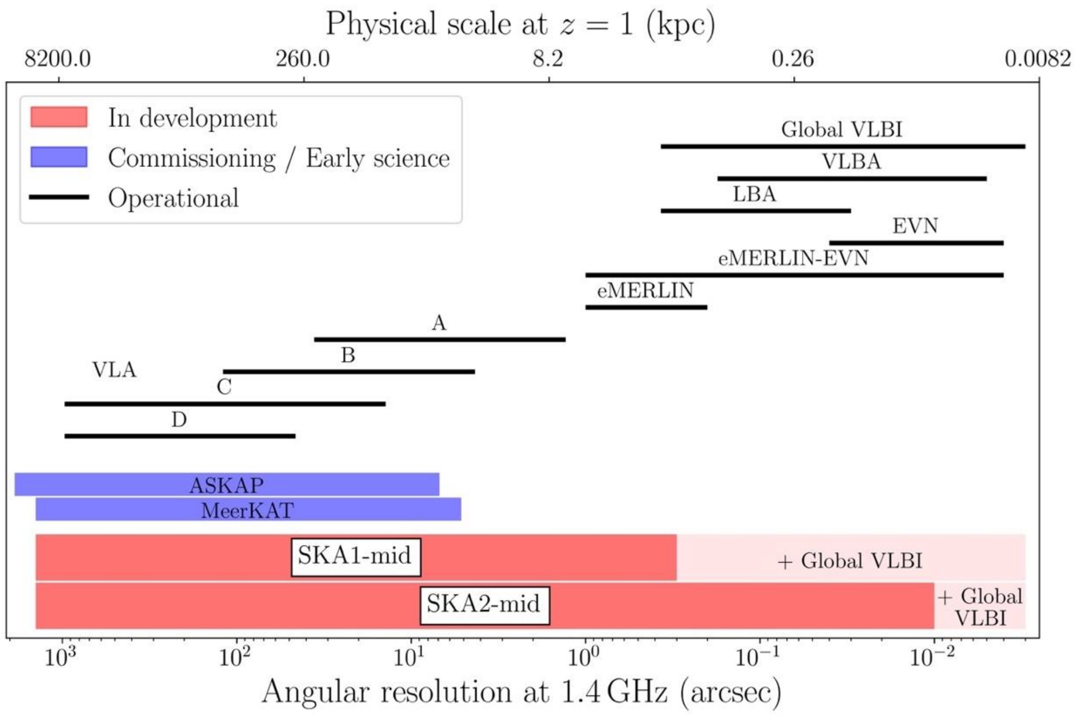
Additionally, SKA-VLBI will provide a boost in sensitivity that will allow VLBI surveys of the sub-mJy source population and access to the µJy regime for individual sources, with improved fidelity due to the SKA superior amplitude and polarization calibration. It will also provide multi-beam capability for enhanced phase referencing techniques, transients localisation, piggyback onto SKA1 surveys of targeted sources, etc. (Paragi et al. 2015 [RD1], and references therein). The advantageous location of the SKA telescopes will allow access to the Southern Hemisphere sky and the galactic centre.

Figure 3. SKA Telescope angular resolution compared to other radio interferometers *(original idea @Radcliffe2018).*



The SKA project is supported by a wide international collaboration, that during the design of the first phase, SKA1, has been organised into different Consortia, each responsible for the design of a distinctive component or element of the telescopes, e.g. dishes, correlator, signal and data transport, etc. At the time of writing, this design is being finalised with the Critical Design Reviews (CDRs) of the different elements, nearing completion. Once the elements designs have been evaluated, the Consortia dissolve and the Bridging Phase starts with support from the former participant institutions to prepare for a System Level Critical Design Review to assess the design of the full SKA1 Observatory and to lead towards construction.

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3 JUMPING JIVE WP10 Deliverable D10.1 description

The VLBI capability of the SKA1 Observatory relies on the proper functioning, interface and coordination between each of the telescopes, its different elements and a VLBI element. The VLBI element is comprised by externally supplied VLBI equipment (a.k.a. VLBI Terminal), that will provide the buffering and streaming capability to send SKA VLBI data to an external VLBI correlator and all necessary interfaces for scheduling and conducting the VLBI observations. The VLBI Terminal does not belong to the SKA Observatory, it is considered as third-party equipment that will be provided by an international VLBI Consortium.

The level of detail of the VLBI element described in this deliverable is enough to properly define the interfaces with the SKA1 telescopes. The solution presented best fits the present scenario, but some details may be subject to change, as at the time of writing, the SKA1 Project still needs to complete CDRs for several VLBI related elements (e.g. Low Frequency Aperture Array, Science Data Processor, etc.) and the System Level CDR itself where certain System Level aspects will be clarified. During the already initiated SKA1 Bridging Phase the interfaces will be finalized, solving any remaining uncertainties. The design solution for the VLBI capability will be presented as an Engineering Change Proposal to the SKA Project Configuration Control Board for approval to be ready for System Level CDR planned for third quarter of 2019. No additional cost drivers are anticipated as the elements have already implemented, or are including, any necessary changes in their design for their CDR closeout.

This deliverable D10.1, "VLBI Interfaces with SKA Consortia", consists of the following documents:

- Details on VLBI Interfaces with SKA Consortia (present report)
- External Interface Control Document between SKA1 to VLBI (Annex 1)
- External Interface Control Documents between SKA1 Consortia to VLBI (Annex 2, 6 documents):
  - LOW Central Signal Processor (CSP) to VLBI EICD (Annex 2.1)
  - MID Central Signal Processor (CSP) to VLBI EICD (Annex 2.2)
  - Telescope Manager (TM) to VLBI EICD (Annex 2.3)
  - LOW Signal and Data Transport (SaDT) to VLBI EICD (Annex 2.4)
  - MID Signal and Data Transport (SaDT) to VLBI EICD (Annex 2.5)
  - MID Science Data Processor (SDP) to VLBI EICD (Annex 2.6)
- VLBI System Level Requirements review report (Annex 3)
- SKA1 Critical Design Reviews outcomes for the VLBI Capability (Annex 4)

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4 VLBI with SKA1

VLBI is an observing mode of the SKA Observatory with the aim to facilitate the participation of the SKA1 LOW and MID telescopes in Global VLBI observations. The SKA1 provides multiple ultra-sensitive VLBI tied-array beams for inclusion in VLBI observations. Each SKA1 VLBI beam acts as an individual element in the VLBI network, equivalent to an individual single beam radio telescope participating in the observation. Tied-array beams are produced by a Beamformer in the SKA correlator utilising some subset (or subarray) of LOW stations or MID dishes by coherently combining the signals from the receptors such that the combined gain is directed at a specified point on the sky. This mode provides at least 4 dual-polarisation VLBI beams formed from one or more subarrays and is compatible with the standard VLBI observing modes.

The final purpose of the VLBI mode is to provide images of the sky at µJy noise levels and (sub-)milliarcsecond angular resolution, complementing the SKA1 angular resolution. The SKA Observatory Data Products for this mode are VLBI beams formatted into VDIF packets to be correlated at an External Correlator, the associated metadata and image cubes produced from the same subarray to provide calibration for the VLBI data, as well as to complement the science data return by providing images of the radio sources at different angular and spectral resolutions.

The key operational concepts of the SKA Observatory [RD2] that define how the VLBI operations will be performed are:

- the configuration and simultaneous operation of independent subarrays, to be used for different purposes, e.g. engineering tasks, commissioning of a new receiver, observing simultaneously at different bands with different sensitivity, angular and spectral resolutions, etc.
- the simultaneity of Imaging and VLBI observing modes in the same subarray for calibration and commensal science, and
- the independent multi-beam capability for each subarray.

Inclusion of multi-beam radio telescopes in the VLBI networks will challenge the correlation paradigm, introducing multiple phase centres and very limited fields of view (FoV) compared with the current single-beam radio telescopes contribution. One of the advantages of using the multi-beam (or "multi-view") capability (Figure 4) is the enhancement of the phase referencing observational technique observing simultaneously the target and several surrounding calibrators for full 2D correction of the spatial atmosphere distortions around the target, relaxing the maximum allowed distance to the calibrators by an order of magnitude with respect to single beam telescopes requirements (Rioja et al. 2009 [RD3]).

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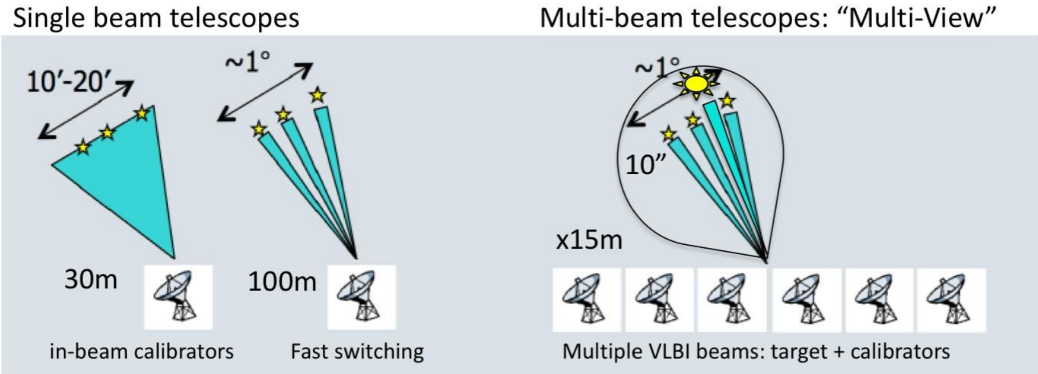
Figure 4. VLBI with multi-beam vs. single-beam radio telescopes.



The VLBI observing mode needs proper functioning and coordination of all the different elements of the SKA1 telescopes. The VLBI Operational workflow is as follows (Figure 5):

- Whenever a Principal Investigator (PI) sends a VLBI proposal to the SKA Observatory, if approved, it becomes an Observatory Project. The PI will provide all necessary information for the Observation Design, in particular the VEX file (version 2.0) that describes all details needed to perform the VLBI observation and to correlate it [RD4]. With this information the observation is planned and scheduled, and a Scheduling Block (SB) is generated for observation execution. These functions are performed by the Telescope Manager (TM) element.

- Digitised signal from the LOW antennas grouped in stations with 256 individual elements and from the MID dishes, is fed into the Correlator BeamFormers (CBF) of the Central Signal Processor (CSP), for each SKA1 telescope. Apart from complex correlation, the correlators form VLBI, Pulsar Timing and Pulsar Search tied-array beams. In particular VLBI beams are corrected for polarization impurity and RFI effects, are channelized in real representation, and formatted into VDIF packets (VLBI standard for data interchange format [RD5]).

- Correlator visibilities are received by the Science Data Processor (SDP) and are processed by the real-time calibration pipeline to produce and feed back to the correlator the beamforming calibration parameters (delay models, complex gains, Jones matrices, etc.), via the metadata flow managed by the TM. The real-time calibration must be determined and applied to maximise the coherent tied-array beam gain as well as its polarisation purity while counteracting possible ionospheric position jitter. Visibilities are also processed by SDP to produce images cubes that are sent to the SKA Regional Centres (SRCs) for subsequent processing and analysis.

- VLBI VDIF packets are sent to the VLBI Terminal located at the Science Processing Centre (SPC) for either real-time streaming to the External correlator (e-VLBI mode) or for recording (buffering) and streaming after the observation has been performed. e-VLBI mode has several advantages with respect to the recorded mode, such as real-time fringe verification and troubleshooting, fast scientific turnaround, observing configuration adaptability, etc. The VLBI Terminal has access to the Observatory metadata via subscription to the TM element to

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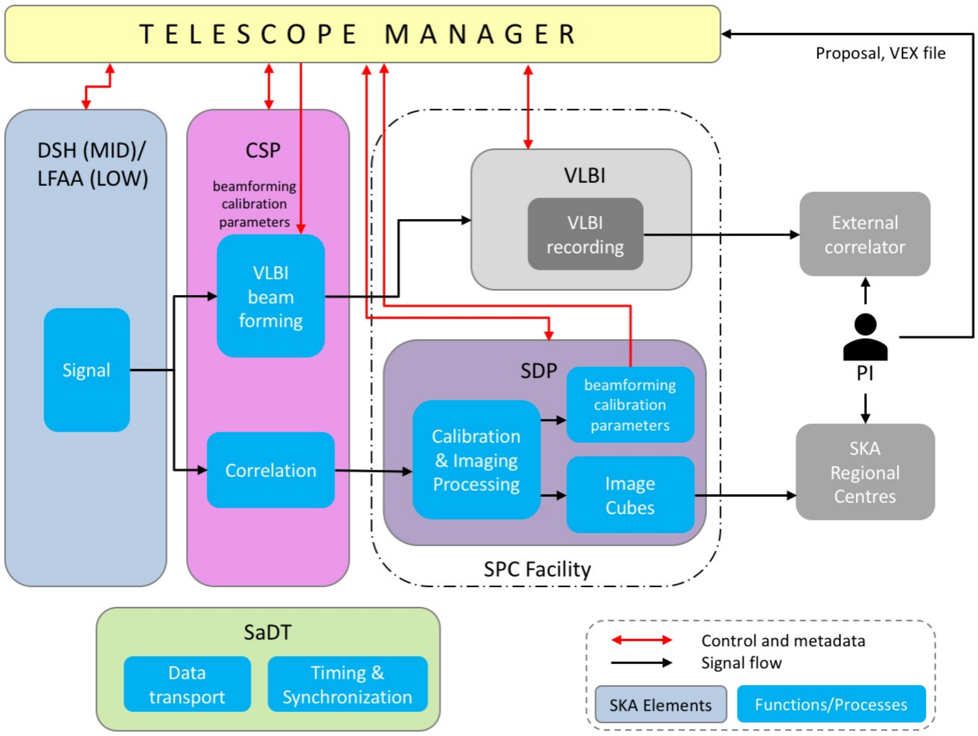
generate an observing log in support for the external correlation and imaging post-processing calibration.

- In parallel, the Signal and Data Transport (SaDT) element is responsible for the science data and non-science data communications links, that route VLBI data to the VLBI Terminal from the correlators and connect with TM for monitor and control tasks. The SaDT element is also responsible for the realisation of the SKA timescale based on the use of hydrogen masers which provide a phase-coherent reference signal with the stability required by VLBI.

- The PI accesses the data products from the external correlator (VLBI visibilities, pipeline products including VLBI images and metadata) and from the SRCs (images in support of VLBI calibration and, if included in the VLBI proposal, full resolution imaging data products from the same subarray and/or the whole array).

Figure 5. VLBI Capability Integration in the SKA1 Observatory for LOW and MID telescopes.



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4.1 VLBI with SKA1-MID

The SKA1-MID correlator and beamformer is an FX-type FPGA based correlator with a very flexible architecture that efficiently manages its processing resources [RD6]. It is able to simultaneously process up to 16 independent subarrays, as well as all observing modes simultaneously within each subarray. To do so requires a bandwidth sacrifice, especially for Band 5. The architecture allows input from 200 antennas separated by several 1000s km and can be easily upgraded to support 20% more antennas.

The MID correlator is required to form 1500 beams in different directions for the purpose of Pulsar Search (PSS), 16 beams for Pulsar Timing (PST) and 4 beams for VLBI, from the same or different subarrays. The VLBI tied-array beams can be formed using different subarray sizes, up to the full array size, with the caveat that longer baselines will suffer from coherence losses and the beams will provide limited FoV.

The VLBI capability of MID surpasses that in the System Level L1 requirements [RD7] and provides a total of 520 VLBI beams of 200 MHz effective bandwidth in dual polarisation. Each subarray can produce a maximum of 52 beams of 200 MHz effective bandwidth, or less number of beams with larger bandwidths, e.g. 4 beams of 2.5 GHz bandwidth in dual polarisation (Figure 6). The VLBI beams can be pointed at different positions on the sky within the primary beam of the MID antennas.

Each VLBI beam is corrected for RFI contamination and polarisation leakage at the 200 MHz level, and is channelised in up to 4 dual polarisation beam channels (i.e. subbands in VLBI jargon), with a tunable centre frequency, and bandwidths ranging from 1 to 128 MHz and up to the full 200 MHz bandwidth, using 2 to 16 bits per sample and Nyquist sampling. Beam channels are formatted in VDIF packets using real representation, that are streamed to the VLBI Terminal. Power levels in the beam channels are provided as part of the metadata, as well as beamforming weights.

Together with VLBI beams, MID correlator provides visibility data at reduced spectral resolution compared to normal imaging visibilities, to provide calibration solutions to establish beam coherence and for imaging products in support of VLBI calibration.

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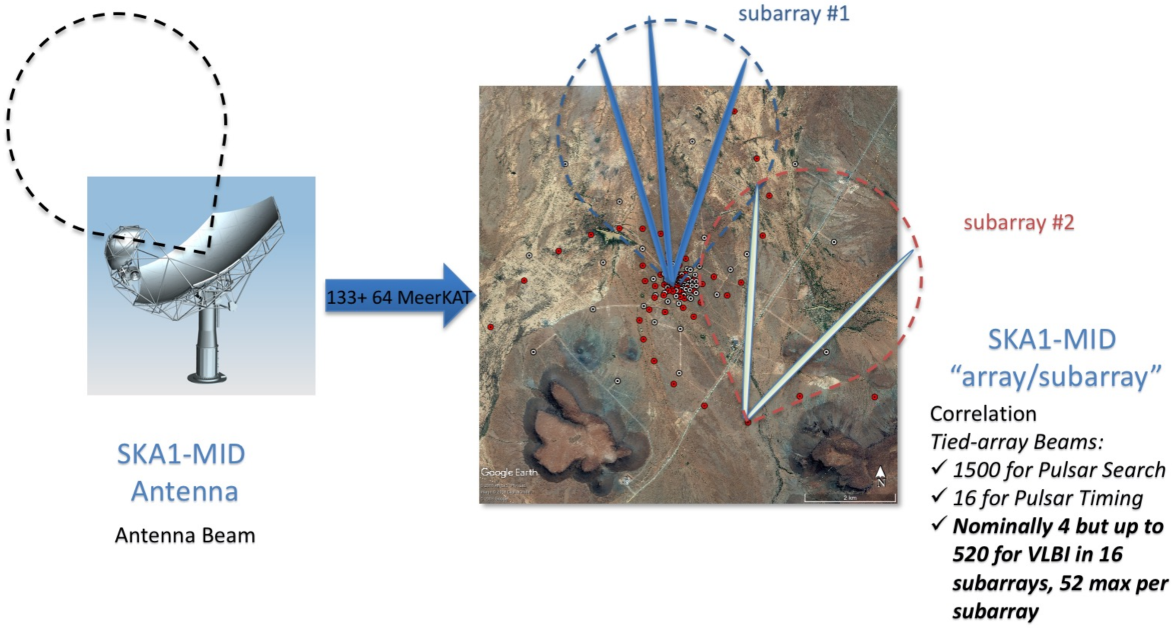
Figure 6. VLBI Capability for SKA1-MID telescope.



Full simultaneity (commensality) of the different observing modes is achieved in all bands for each subarray for moderate observing bandwidths, e.g. 800 MHz per polarisation and beam (Figure 7). But as processing resources are limited, with only 26 FPGA based MID Processors (FSPs) available in the current design, a compromise in bandwidth is required for Band 5 observations. For full bandwidth Band 5 imaging, all correlator resources are required.

Figure 7. SKA1-MID observing commensality.

Band	VLBI + coarse Vis	Imaging	PSS	PST	Zoom
Band 1 (0.35-1.05GHz)	4beams full (700MHz) (8 FSP)	Full (4 FSP)	1500b 300MHz (8 FSP)	16b full (4 FSP)	2 (2 FSP)
	4b 600MHz (6 FSP)	Full (4 FSP)	1500b 300MHz (8 FSP)	16b full (4 FSP)	4 (4 FSP)
Band 2 (0.95-1.76GHz)	4beams full (810MHz) (10 FSP)	Full (5 FSP)	1500b 300MHz (8 FSP)	16b 600 MHz (3 FSP)	⊘
	4b 600MHz (6 FSP)	Full (5 FSP)	1500b 300MHz (8 FSP)	16b full (5 FSP)	2 (2 FSP)
Band 5a/b (4.6-8.5GHz & 8.3-15.3GHz)	2beams 5GHz (26 FSP)	⊘	⊘	⊘	⊘
	4beams 2.5GHz (26 FSP)	⊘	⊘	⊘	⊘
	4beams 600MHz (6 FSP)	512MHz (3 FSP)	1500b 300MHz (8 FSP)	16b 512 MHz (3 FSP)	6 (6 FSP)
	⊘	Full (26 FSP)	⊘	⊘	⊘

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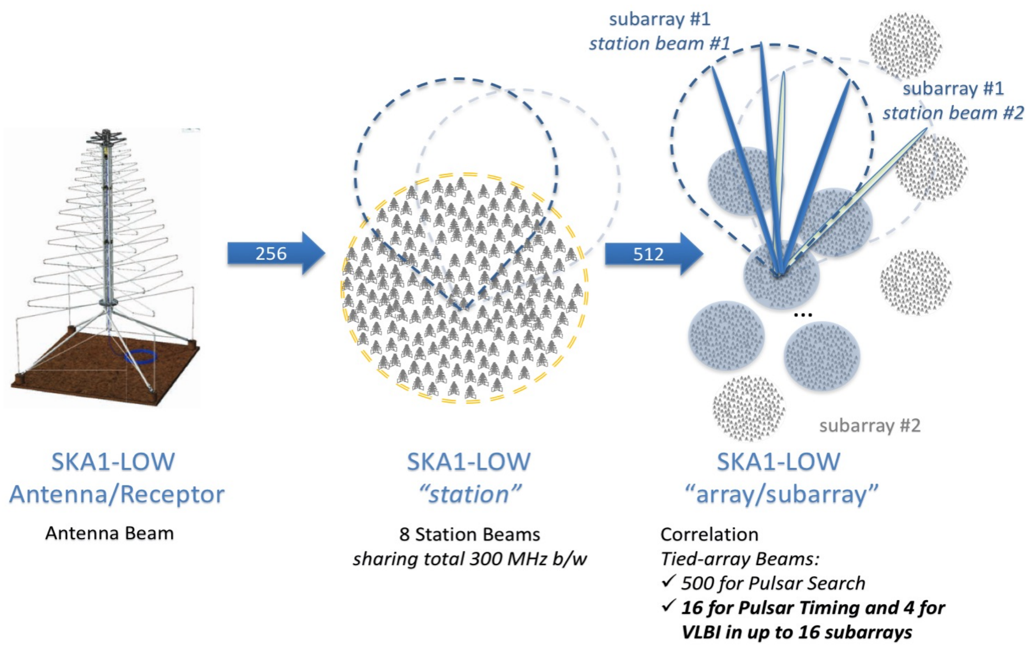
4.2 VLBI with SKA1-LOW

The SKA1-LOW correlator and beamformer is also an FX-type FPGA based correlator that is not as limited by processing resources as the bandwidth to be processed is much narrower (300 MHz bandwidth within the 50-350 MHz observing band) [RD6]. The resources required are available to provide all different processing modes for each subarray simultaneously, for up to 16 independent subarrays.

The LOW correlator is required to form 500 beams in different directions for the purpose of PSS, 16 beams for PST and 4 beams for VLBI, from the same or different subarrays (Figure 8). The tied-array beams can be formed using a subarray formed from all the stations within an aperture of 20 km, and from just one station beam provided by the LFAA element. The beamforming process for PST and VLBI beams is exactly the same, sharing the resources for up to 16 beams. In principle VLBI requires the use of 4 PST beams but it could process more if they are not used by PST.

The VLBI beams can be pointed at different positions in the sky, with a maximum bandwidth of 256 MHz per polarisation and beam. Each VLBI beam is corrected by RFI contamination and polarisation leakage before beamforming at the LFAA fine channel level and is channelised in up to 4 dual polarisation beam channels contiguous in frequency, with a tunable centre frequency and bandwidths ranging from 1 to 64 MHz, using 2 to 8 bits per sample and Nyquist sampling (and oversampling). Beam channels are formatted in VDIF packets using real representation, that are streamed to the VLBI Terminal. Power levels in the beam channels are provided as part of the metadata, as well as beamforming weights.

Figure 8. VLBI Capability for SKA1-LOW telescope.



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4.3 VLBI Element description

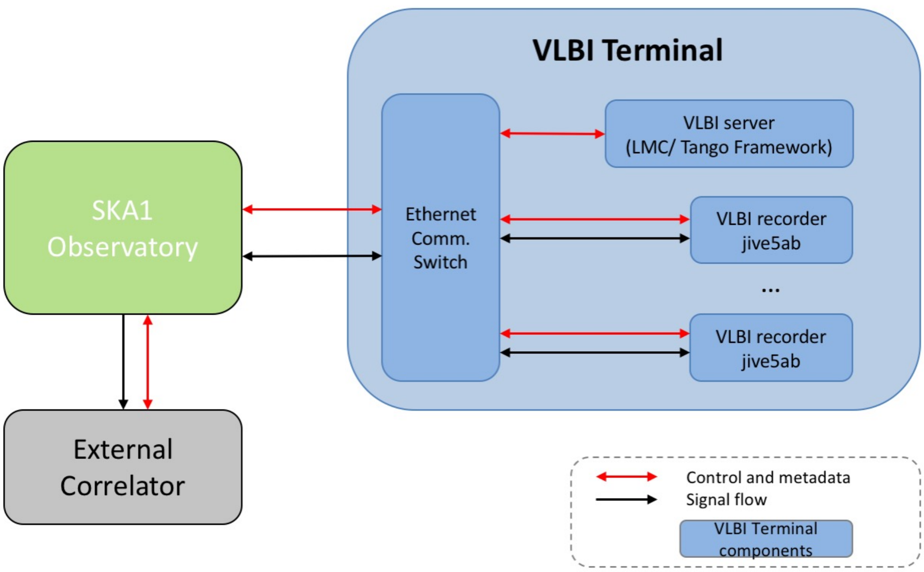
The VLBI Element (Annex 1) provides the buffering and streaming capability to send SKA VLBI data to an external VLBI correlator, as well as all necessary interfaces for scheduling and conducting the VLBI observations. It is composed by the following sub-elements:

- VLBI Terminal containing the VLBI VDIF recorders.
- VLBI proposal and VEX 2.0 file parser script to generate SKA1 scheduling blocks.
- VLBI Terminal Local Monitoring and Control (LMC).

The VLBI Terminal to be provided for the SKA1 telescope will be third-party equipment, under the responsibility of an international VLBI Consortium. To allow easy access for the VLBI consortium and to not impose additional burden to the very restricted radio frequency interference control at the telescopes sites [RD8], the terminal will be installed at the Science Processing Centres (SPC), located in Perth and Cape Town for SKA1-LOW and SKA1-MID, respectively.

The VLBI Terminal will be comprised of a COTS VLBI server, a COTS 100GE Ethernet Switch and one or several COTS VLBI recorders (Figure 9). The exact number of recorders depends on the recorders performance and on the required recording data rate, with the aim to support 400 Gbps (MID) and 100 Gbps (LOW) maximum data rates that will be provided by the SKA1 telescopes with the agreed interfaces. The data rate could easily surpass this initial capability, mainly for MID Band 5, therefore the VLBI equipment and interfaces will be gradually upgraded during the lifetime of the SKA Observatory.

Figure 9. VLBI Terminal description.



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The Ethernet switch will provide bi-directional communication with the SKA1 Observatory and from there, with the outside world. The ethernet switch will receive the VLBI VDIF packets from the correlators, in the specific VDIF format to be used by SKA, and either send them to the External correlator in real-time for e-VLBI observing or stream them to the VLBI recorders for subsequent playback at a convenient time. It will also communicate with the Telescope Manager for monitor and control tasks and subscription to metadata. The communication with the outside world also provides access for developers for hardware and software maintenance tasks and upgrades.

The VLBI VDIF recorders selected for this design are FlexBuff type recorders but other types of compatible VDIF recorders may be used in conjunction or alternatively (e.g. Mark 6 Haystack recorders or NAOJ OCTAVE-families). FlexBuff recorders provide a flexible and standard COTS solution to receive, buffer (record) and transmit VLBI data streams in a simultaneous way. A FlexBuff recorder consists of a COTS server containing a buffer size to store data. Requirements for a FlexBuff vary depending on the buffer capacity and the sustained data rate that needs to be achieved [RD9]. The solution presented in this study (Annex 1) is able to support the typical number of Global VLBI Observations supported during every EVN Observing Session (approximately 30% of the total). The VLBI recorders are controlled using the jive5ab open source control software [RD10].

The VLBI server will implement SKA1 Local Monitoring and Control (LMC) within a Tango framework described in the TM to VLBI ICD (Annex 2.3). Tango is an open source framework adopted by the SKA1 Observatory for Monitor and Control of all the different sub-elements and elements. The LMC will be responsible for Monitor and Control of the VLBI terminal and for subscription to the appropriate metadata, as well as logging events and sending alarms to the Telescope Manager (Figure 10). The VLBI server will implement an additional bespoke application to extract the metadata and generate the observing experiment log required by the External correlator that will be recorded in the FlexBuff recorders along with the data. The LMC will also implement a translator for jive5ab commands to control the recorders and use standard Tango translators for the Linux server and the Ethernet switch.

During construction the VLBI Consortium will provide a detailed Architectural Design Document and appropriate operational and maintenance manuals for proper inclusion of the VLBI Element in the Operations of the SKA1 Observatory. During steady SKA1 Operations the VLBI Consortium will provide line-replaceable units (LRU) spares for simple O-level (Organizational) maintenance tasks (e.g. buffer units replacement).

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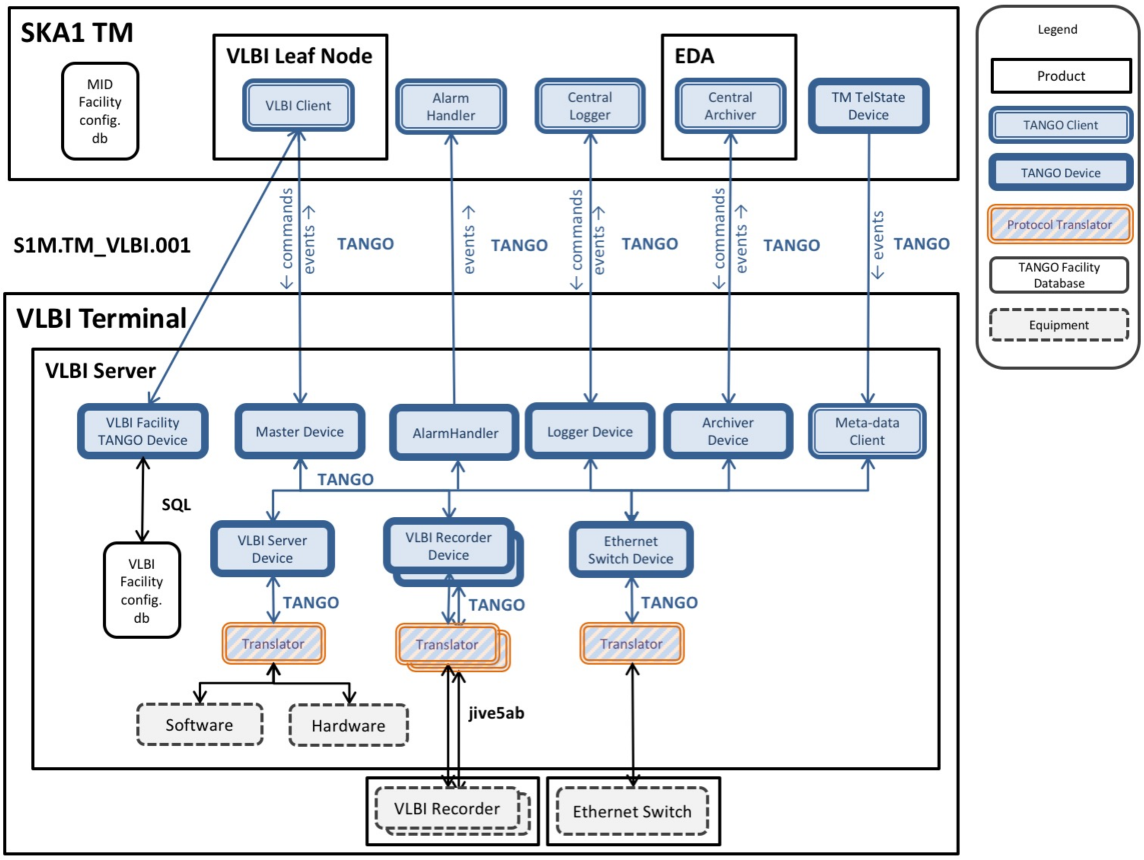
Figure 10. VLBI Terminal Local Monitoring and Control sub-element description.



5 VLBI to SKA Observatory Interfaces

The VLBI Element needs to interface with most of the elements of the SKA1 Observatory. Figure 11 summarizes the different interfaces of the VLBI Element. Whenever the telescope is specified the interfaces are specific to that telescope. If not specified, the interface is common for both telescopes.

The list of interfaces detailed in the External Interface Control Documents (EICD) is the following:

- External VLBI interface with the SKA Observatory (Annex 1). This interface describes the VLBI Element, the particular VDIF data exchange format to be used by the CSP Correlator Beamformer, the information contained in the VEX 2.0 file provided by the PI to generate scheduling blocks (SBs), the jive5ab translator, etc.

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- External Interface with the Science Processing Centre Infrastructure (Annex 1): The detailed interface is not part of this deliverable but will be specified in the SKA1 Observatory agreement for third party equipment to be installed at the SPC facilities. Details of necessary space, rack, power, cooling, etc. are specified in the External VLBI Interface document. This agreement will also provide Internet access to the VLBI Terminal, detailing the connections to the SPC external communications router.

- External Interface with the Signal and Data Transport (SaDT) element (Annex 2.4 and 2.5): For both telescopes SaDT will interface with the VLBI Terminal to provide connection to the Non-Science Data Network (NSDN) for monitor and control of the terminal by the Telescope Manager (TM) element and typical network infrastructure services (e.g. NTP). It is anticipated the usage of a 100 GE line for NSDN connection (Figures 12 and 13) to simplify the VLBI Terminal COTS switch selection and the connection via an Edge Security device (i.e. firewall). Details on the NSDN are to be finalised as part of a on-going Bridging activity. SaDT LOW (Annex 2.4) will also interface with the VLBI Terminal to provide the spigot for real-time streaming of the VLBI beam data from the Correlator Beamformer to the VLBI recorders via a Muxponder using a 100 GE dedicated line (Figure 13). For the MID telescope the data spigot is provided by the Science Data Processor (SDP) element.

- External Interface with the Central Signal Processor (CSP) Element (Annex 2.1 and 2.2): there is an interface document for each telescope detailing the VLBI beamformer capabilities and products, specifically the number of VLBI beams, number of channels per beam, bandwidth and central frequency, digitization and sampling, etc.

- External Interface with the Telescope Manager (TM) Element (Annex 2.3): this interface describes the Monitor and Control of the VLBI Terminal, e.g. for set-up and control of the VLBI recorders during the VLBI experiments, monitoring of the VLBI Terminal (e.g. alarms, logging, etc.) and subscription to metadata. For these functions the VLBI Element will implement a Local Monitoring and Control sub-element (VLBI.LMC) using the TANGO control system framework, harmonised with the rest of the SKA1 elements.

- External Interface with the Science Data Processor (SDP) Element (Annex 2.6): this interface provides the data spigot from the MID telescope only. The MID Correlator and Beamformer streams the VLBI beams data using 80x100 GE shared lines from CSP to SDP Elements (Figure 12), interspersing the VLBI VDIF packets with visibilities, transient buffer data, etc. The VDIF packets arrive to the SDP Ingress Ethernet switch and using standard TCP/IP and ARP protocols will be redirected directly to the VLBI Terminal Ethernet communication switch, using 4x100 GE lines, via an Edge Security device (i.e. firewall).

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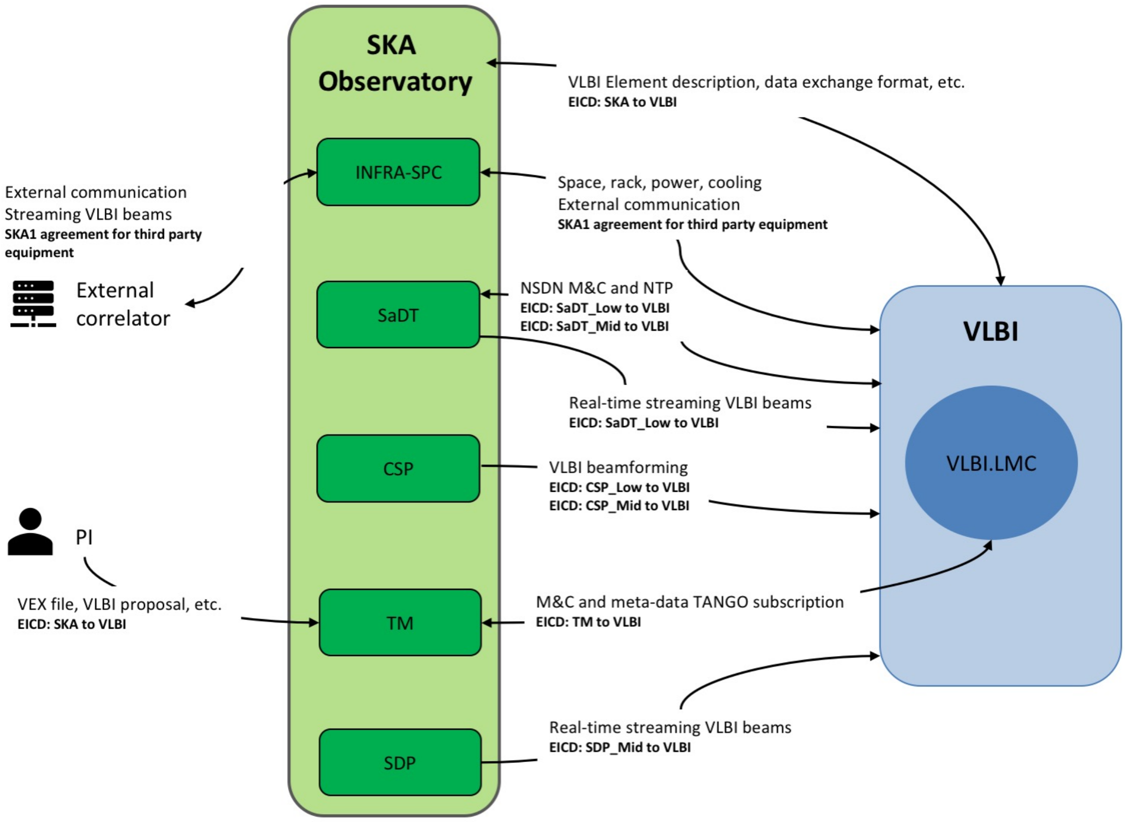
Figure 11. VLBI Interfaces to SKA1 Observatory



5.1 SKA1-MID to VLBI Interfaces

Figure 12 summarizes the VLBI Interface Topology with the SKA1-MID telescope starting from the CSP element that produces the VLBI data streams to the VLBI Terminal and towards the external correlator (Annex 1). External VLBI equipment stakeholders are responsible for the data and control links from the last SKA1 interface point to the location of the external VLBI equipment in the designated place in the Science Processing Centre and to the SPC external router (dashed lines).

The distinctive feature for the MID topology is the usage of the 80x100 GE shared data lines from the correlator to the SDP to send the VLBI beam data together with visibilities and other data products. This decision gives greater flexibility to allow the correlator to produce and send higher data rates for VLBI and is more cost effective than using dedicated lines for VLBI data, that could only be used when a VLBI observation is taking place. But this solution implies an additional interface with SDP.

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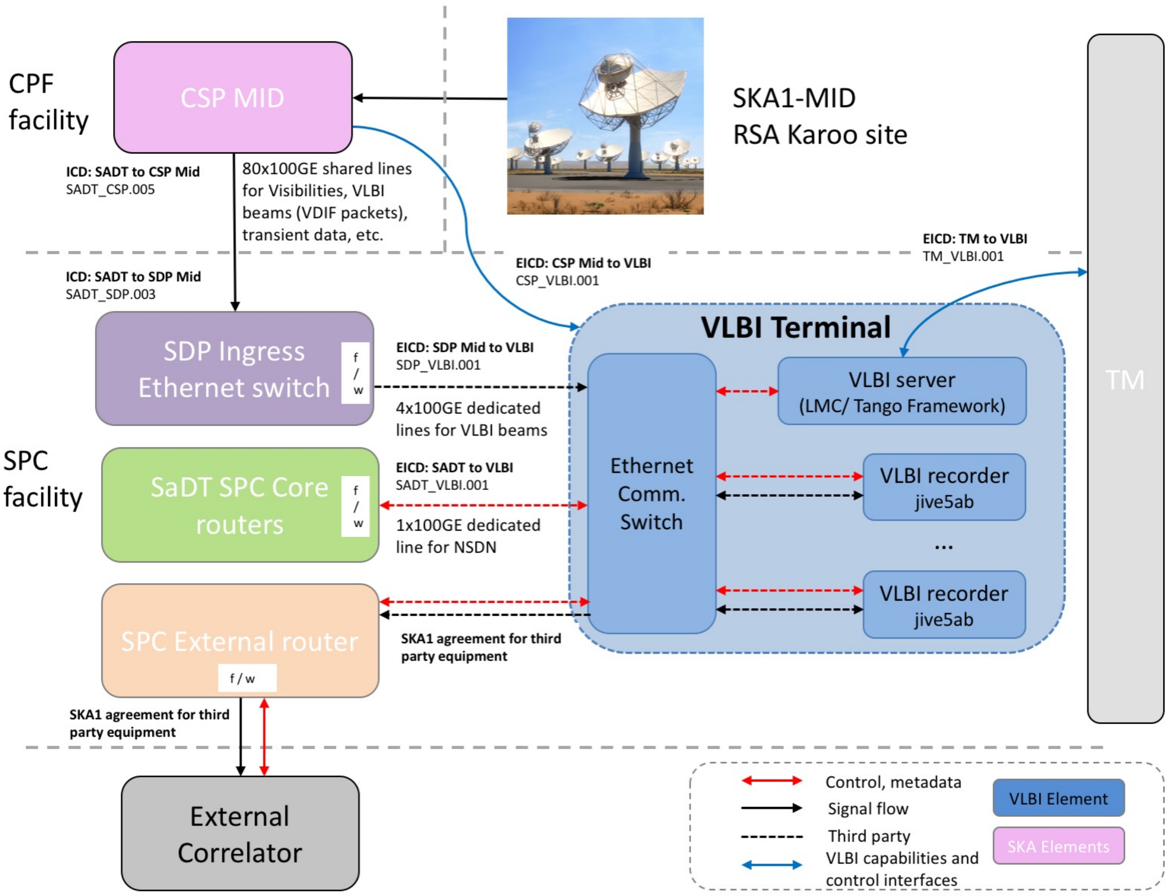
Figure 12. VLBI Interface Topology with SKA1 MID Telescope



5.2 SKA1-LOW to VLBI Interfaces

Figure 13 summarizes the VLBI Interface Topology with the SKA1-MID telescope starting from the CSP element that produces the VLBI data streams to the VLBI Terminal and towards the external correlator (Annex 1). External VLBI equipment stakeholders are responsible for the data and control links from the last SKA1 interface point to the location of the external VLBI equipment in the designated place in the Science Processing Centre and to the SPC external router (dashed lines).

The distinctive feature for the LOW topology is the usage of a 1x100 GE dedicated data line from the correlator to the SPC Facility to send the VLBI beam data. This solution implies a direct interface between SaDT to the VLBI Terminal.

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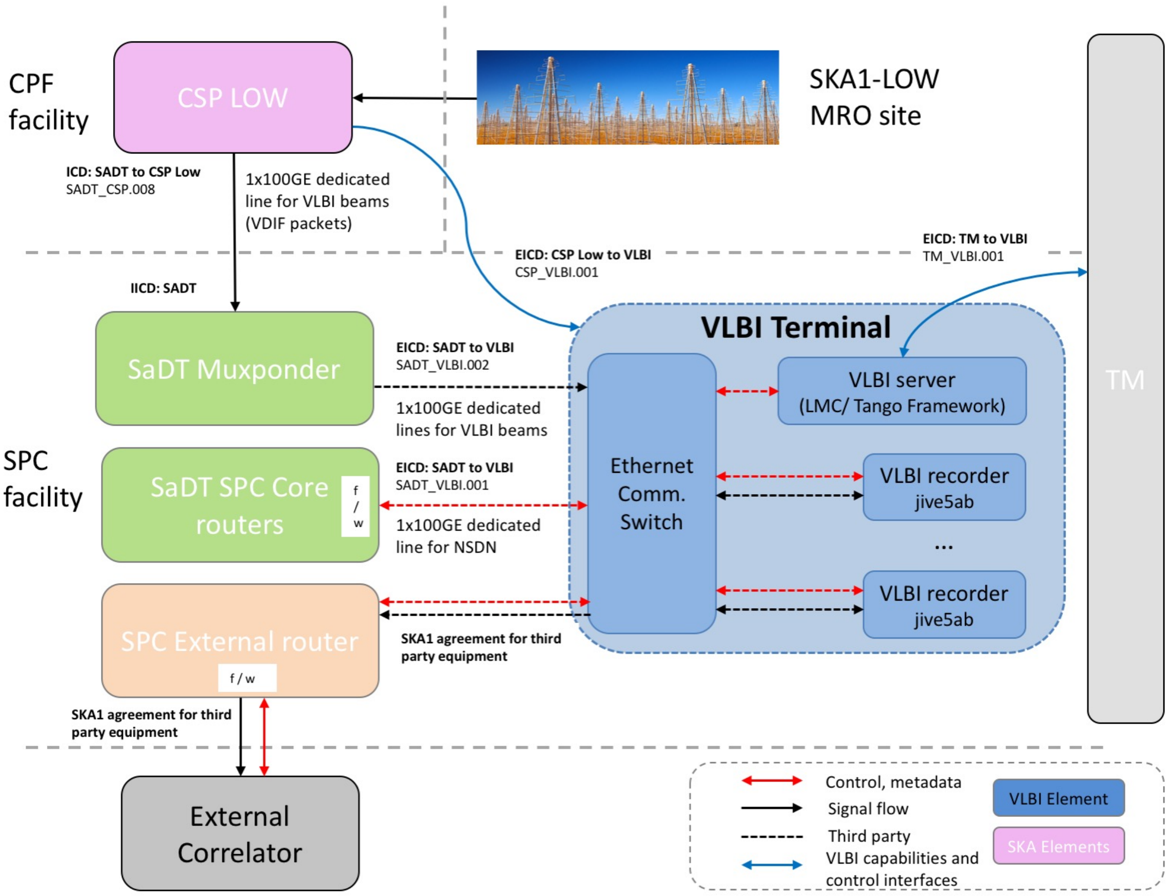
Figure 13. VLBI Interface Topology with SKA1 LOW Telescope



6 SKA1 VLBI System Level Requirements

The high-level quantitative and qualitative characteristics of the SKA Phase 1 System are captured in the form of formal requirements (Level 1 System requirements) that are allocated to each of its constituent elements. A basic set of VLBI requirements and related requirements are provided in the SKA Phase 1 System Requirements Specification Revision 11 [RD7], but this set was considered incomplete, specifically:

- Implementation and refinement of requirements from the Engineering Change Request ECP140008 for VLBI with SKA1-MID was incomplete.
- Review and definition of detailed and new VLBI requirements needed to be performed, including outcomes from the Engineering Change Request ECP160040 for VLBI with SKA1-LOW.
- Requirements needed to be harmonized between SKA1-LOW and SKA1-MID.
- VLBI related elements interface requirements needed attention.
- SKA1 to VLBI External interface requirements needed to be included.

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A review of the justification, consistency and identification of gaps in the Level 1 VLBI related System requirements has been carried out, ensuring appropriate flow down into design requirements (Level 2 and Level 3 requirements) for the different SKA1 elements (Annex 3). Special attention was required for the SKA1 LOW telescope as the VLBI capability was only recently introduced into its design.

The outcomes presented in this review are the result of consultation with the members of the VLBI science working group, discussions held with involved SKA Consortia during CDRs (Section 7, Annex 4), and discussions held with the VLBI Consortium representatives (lead by JIVE). Additionally, the assumptions raised by the different elements on VLBI L1 System level requirements are also informing this study, whenever pertinent.

As a result, 33 new VLBI requirements are proposed to be added and 40 of the original 66 requirements need amendment. These requirements are subjected to approval by the SKAO Configuration Control Board (CCB) via the Engineering Change Proposal (ECP) process.

All SKA1 elements are compliant with the new proposed requirements. There is only one requirement for beamforming, considered as useful, that is not included in the SKA1 design (i.e. direction-dependent corrections for beamforming).

The list of new proposed requirements that can be divided in different categories and are summarized in Tables 6-1 to 6-6 below.

Table 6-1: Observing mode and Commensality requirements:

SKA1-SYS_REQ	Requirement	Reference
NEW	**VLBI Observing**	SKA1 Operational Concept Document SKA-TEL-SKO-0000307 Rev3 [RD2]
NEW	**VLBI Observing Modes**	SKA1 Operational Concept Document SKA-TEL-SKO-0000307 Rev3 [RD2]

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Table 6-2: Scheduling requirements:

SKA1-SYS_REQ	Requirement	Reference
NEW	**VLBI Observing Projects**	SKA1 Operational Concept Document SKA-TEL-SKO-0000307 Rev3 [RD2]
NEW	**VLBI Observing Projects Updates**	SKA1 Operational Concept Document SKA-TEL-SKO-0000307 Rev3 [RD2]

Table 6-3: Tied array beams generic requirements:

SKA1-SYS_REQ	Requirement	Reference
NEW	**Tied array beams from subarrays**	SKA1 Operational Concept Document SKA-TEL-SKO-0000307 Rev3 [RD2]
NEW	**Direction-dependent corrections for beamforming (Useful)**	Discussions with VLBI Science Working Group
NEW	**SKA1_Low tied-array beams: store time-dependent station weights**	Alignment SKA1-MID and SKA1-LOW, discussions with VLBI Science Working Group
NEW	**SKA1_Low: Tied array beams constrained to a single station beam**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]
NEW	**SKA1_Low multi-beam simultaneity**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]

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Table 6-4: VLBI beams-channels requirements (for both Mid and Low):

SKA1-SYS_REQ	Requirement	Reference
NEW	**SKA1_Low number of beam-channels per VLBI beam** **SKA1_Mid number of beam channels per VLBI beam**	SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116 (Annex 1)
NEW	**SKA1_Low VLBI beam-channels bandpass ripple** **SKA1_Mid VLBI beam channel bandpass ripple**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]
NEW	**SKA1_Low VLBI beam-channel frequency response** **SKA1_Mid VLBI beam channel frequency response**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]
NEW	**SKA1_Low VLBI beam-channel temporal impulse response** **SKA1_Mid VLBI beam channel temporal impulse response**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]
NEW	**SKA1_Low VLBI beam channel output real representation** **SKA1_Mid VLBI beam channel output real representation**	SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116 (Annex 1)
NEW	**SKA1_Low VLBI beam channel power level** **SKA1_Mid VLBI beam channel power level**	SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116 (Annex 1)
NEW	**SKA1_Low VLBI beam channel RFI flagging**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]

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NEW	**SKA1_Low VLBI beam polarization calibration**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]
NEW	**SKA1_Mid VLBI beam channel amplitude RFI-flagging invariant**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]
NEW	**SKA1_Mid VLBI beam polarization calibration**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]
NEW	**SKA1_Mid VLBI per-antenna, per-beam polarization calibration (Useful)**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]
NEW	**SKA1_Mid VLBI beam channel polarization calibration (Useful)**	SKA1 CSP Element Requirements Specifications SKA-TEL-CSP-0000010 Rev 6 [R11]

Table 6-5: Frequency standard and timescale related requirements:

SKA1-SYS_REQ	**Requirement**	**Reference**
NEW	**Steering to UTC for VLBI**	Discussions with VLBI Science Working Group
NEW	**SKA1_Mid Sample Clock Frequency Offset for VLBI**	Discussions with VLBI Science Working Group

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Table 6-6: VLBI terminal requirements:

SKA1-SYS_REQ	Requirement	Reference
NEW	**VLBI Terminal Monitor and Control**	SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116 (Annex 1)
NEW	**VLBI equipment internet access**	SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116 (Annex 1)
NEW	**SKA1_Low: Noise power reporting interval** **SKA1_Mid: Noise power reporting interval**	SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116 (Annex 1)

7 SKA1 Critical Design Reviews Outcomes for the VLBI Capability

The SKA VLBI scientist working for JUMPING JIVE WP10 has actively participated in all CDRs conducted thus far (with VLBI content), either as a panel member or as a reviewer. In particular, the SKA VLBI scientist has participated in CDRs for: the Correlator and Beamformer sub-element for LOW and MID, the Telescope Manager, the Signal and Data Transport, the Central Signal Processor and the Science Data Processor (preliminary CDR). The outcome from these reviews is positive, indicating that VLBI capability is mature for both LOW and MID SKA telescope designs. Certain technical aspects have been clarified and captured in Interface Control Documents between the different SKA1 elements for the provision and support of VLBI. Any necessary modification to the design has already been included for each element CDR closeout, with just a few exceptions (e.g. general NSDN network design will be finalised during the Bridging phase).

Annex 4 summarizes the outcomes of the SKA1 CDRs with respect to the VLBI capability. At the time of writing, the reviews for LFAA, DSH and SDP elements have not been conducted yet.

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References

[RD1] Paragi et al., Proceedings of Advancing Astrophysics with the Square Kilometre Array (AASKA14). 9 -13 June, 2014. Giardini Naxos, Italy. Online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215, id.143

[RD2] SKA1 Operational Concept Document, SKA-TEL-SKO-0000307, Rev 3

[RD3] Rioja, M., Dodson, R., Porcas, R. W. et al. 2009, PoS(EXPReS09)014

[RD4] VEX 2.0 file format, https://safe.nrao.edu/wiki/bin/view/VLBA/Vex2doc

[RD5] VLBI Data Interchange Format (VDIF) Specification, Release 1.1.1, June 2014, http://vlbi.org/vdif/docs/VDIF_specification_Release_1.1.1.pdf

[RD6] SKA1 CSP Element Architectural Design Document, SKA-TEL-CSP-0000014, Rev 4

[RD7] SKA Phase 1 System Requirements Specification, SKA-TEL-SKO-0000008, Rev 11

[RD8] SKA EMI/EMC Standards, Related Procedures & Guidelines, SKA-TEL-SKO-0000202, Rev 3

[RD9] Hardware design document for simultaneous I/O storage elements, NEXPReS Deliverable D8.2, http://www.jive.nl/nexpres/lib/exe/fetch.php?media=nexpres:2011-02-28_wp8-d8.2.pdf

[R10] Jive5ab command set 1.10 http://www.jive.nl/~verkout/evlbi/jive5ab-documentation-1.10.pdf

[R11] SKA1 CSP Element Requirements Specifications, SKA-TEL-CSP-0000010, Rev 6

[RD12] SKA1 Scientific Use Cases, SKA-TEL-SKO-0000015, Rev 3

ANNEXES

ANNEX 1: SKA1 External Interface Control Document to VLBI

SKA1 TELESCOPE EXTERNAL INTERFACE CONTROL DOCUMENT TO VLBI

Document Number	SKA-TEL-SKO-0000116
Document Type	ICD
Revision	B
Author	C. Garcia Miro
Date	2018-11-26
Document Classification	UNRESTRICTED
Status	Draft

Name	Designation	Affiliation	Signature
Owned by:			
C. Garcia-Miro (on behalf of the VLBI Consortium)	VLBI Scientist	SKA Office	
Released by:			
Approved by:			

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DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2018-11-20	-	First draft as per discussions at JIVE (January and August 2018)
B	2018-11-26		Included comments from VLBI Consortium.

DOCUMENT SOFTWARE

	Package	Version	Filename
Word Processor	MS Word	2018	SKA-TEL-SKO-0000116_1-SKAtoVLBIExternalICD.docx
Block diagrams			
Other			

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington, Macclesfield Cheshire SK11 9DL Registered in England & Wales Company Number: 07881918
Website	www.skatelescope.org

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TABLE OF CONTENTS

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LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AD	Applicable Document
CI	Configuration Item
CSP	Central Science Processor
DDBH	Digital Data Back Haul
ESD	Electrostatic Discharge
FEC	Forward Error Correction
GBASE	Gigabit/Second Baseband
GE	Gigabit Ethernet
ICD	Interface Control Document
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organisation for Standardisation
LC	Little Connector
MAC	Media Access Code
M&C	Monitor and Control
MPO	Multi-fibre Push-On
MTU	Maximum Transmit Unit

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NSDN	Non-Science Data Network
OM4	Optical Multimode 4
OSI	Open Systems Interconnection model (ISO/IEC 7498-1)
PTP	Precision Time Protocol
QSFP	Quad Small Form-factor Pluggable
RD	Reference Document
RFI	Radio Frequency Interference
Rev	Revision
SADT	Signal and Data Transport
SAT	Synchronisation and Timing
SDP	Science Data Processor
SFF	Small Form Factor
SFP	Small form-factor pluggable
SPC	Science Processing Centre
SKA	Square Kilometre Array
SKA1	Phase 1 of the SKA
SKA1-Mid	Mid frequency array of dishes of SKA1
TBC	To be confirmed
TBD	To be decided
TM	Telescope Manager
UDP	User Datagram Protocol
VLBI	Very Long Baseline Interferometry

LIST OF TERMS

Scan – A scan is the atomic unit for CSP signal processing. Certain CSP parameters can change only at scan boundaries, most notably the processing mode and the composition of a sub-array. A Scheduling Block can be executed as a sequence of one or more scans.

A **Very Long Baseline Interferometry (VLBI) "beam"** is directed towards an independent delay centre on the sky, of whatever beamformed bandwidth.

A **VLBI "beam-channel"** is an output spigot (time-series sampled data stream, re-quantized, formatted, and addressed appropriately), sourcing directly or via filtering from one VLBI beam.

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1 INTRODUCTION

1.1 Scope and Purpose

This document provides details about the VLBI Element that is comprised by externally supplied VLBI Equipment and the different interfaces with the SKA1 Observatory for scheduling and conducting the VLBI Observations. This document provides context and necessary information for the different SKA1 Elements that interface with the VLBI Element, in particular:

1. Telescope Manager
2. CSP
3. SaDT
4. SDP
5. SPC INFRA, interfaces managed in the SKA1 Observatory agreement for third party equipment.

The individual interfaces are described in detail in the different Elements to VLBI ICDs. The interfaces with SPC INFRA will be documented in the SKA1 Observatory agreement for third party equipment.

1.2 Boundaries of responsibilities

The SKA Office is the Owner of the SKA1 interfaces, and acts as the authority of the system architecture. The point of contact of the Owner is the SKA Office System Engineer.

The roles and responsibilities are as follows:

Party:	SKAO
Point of contact:	SKA MID/LOW System Engineer
Role:	Interface Leading Party
Responsibilities:	Drive the definition of the ICD
	Submit the ICD for review and approval

Party:	VLBI Consortium
Point of contact:	SKA VLBI Scientist
Role:	Interface Following Party
Responsibilities:	Assist with the definition of the ICD
	Review the ICD
	Approve the ICD

1.3 VLBI Capability Overview

VLBI is one of the observing modes of the SKA1 Observatory, available for both SKA1-LOW and SKA1-MID telescopes. The SKA1 telescopes shall provide multiple tied-array beam capability to be included in the Global VLBI networks as very sensitive elements. VLBI will provide high resolution to many SKA High Priority Science Objectives. VLBI will make use of independent subarrays, commensal observing and independent multi-beam capability.

The VLBI Element described in this interface document is comprised by externally supplied VLBI Equipment (a.k.a. VLBI Terminal), that will provide the buffering and streaming capability to send

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SKA VLBI beam data to an external VLBI correlator and all necessary interfaces for scheduling and conducting the VLBI observations.

For VLBI observing mode to properly work it needs the proper and coordinated functioning of all the different SKA1-LOW and MID Elements. Figure 1 shows a high-level diagram showing the responsibilities of the different elements:

- Whenever a Principal Investigator (PI) sends a VLBI proposal to the SKA Observatory, if approved, it becomes an Observatory Project. The PI will provide all necessary information for the Observation Design, in particular the VEX file. With this information the observation is planned and scheduled, and a Scheduling Block (SB) is generated for observation execution. All these functions are performed by the Observatory Science Operations sub-element that is part of the Telescope Manager (TM) Element.

- Digitised signal from the MID dishes and LFAA stations beams is fed into the Correlator beamformer (CBF) sub-element of the Central Signal Processor (CSP), for each SKA1 telescope. Apart from complex correlation of the signal from the different dishes or stations that form the sub-array, the correlators form VLBI, Pulsar Timing and Pulsar Search tied-array beams. In particular VLBI voltage beams are corrected for polarization impurity and RFI effects, are channelized in real representation, and formatted into VDIF packets (VLBI standard for data interchange format).

- Correlator visibilities are received by the Science Data Processor (SDP) and are processed by the real-time calibration pipeline to produce and feed back to the CBF the beamforming calibration parameters (delay models, complex gains, Jones matrices, etc.), via the metadata flow managed by the TM. The real-time calibration must be determined and applied to maximise the coherent tied-array beam gain as well as its polarisation purity while counteracting possible ionospheric position jitter. Visibilities are also processed by SDP to produce image cubes that are sent to the SKA Regional Centres (SRCs) for subsequent processing and analysis.
- VLBI VDIF packets are sent to the VLBI Terminal located at the Science Processing Centre facility for either real-time streaming to the External correlator (e-VLBI mode) or for recording (buffering) and streaming after the observation has been performed. The VLBI Terminal will be monitored and controlled by TM and has access to the Observatory metadata via subscription to generate an Observing log in support for the external correlation and imaging post-processing calibration.

- In parallel, the Signal and Data Transport (SaDT) Element is responsible for the science data and non-science data (e.g. Monitor and Control) communications links between the different Elements, that route VLBI data to the VLBI Terminal from the Correlator Beamformer. The SaDT Element is also responsible for the realisation of the SKA timescale based on the use of hydrogen masers, that provide a phase-coherent reference signal with the stability required by VLBI.

- The PI access the data products from the external correlator (VLBI visibilities, pipeline products including images and metadata) and from the SRCs (images in support of VLBI calibration and, if included in the VLBI proposal, full resolution imaging data products from the same subarray and/or the whole array).

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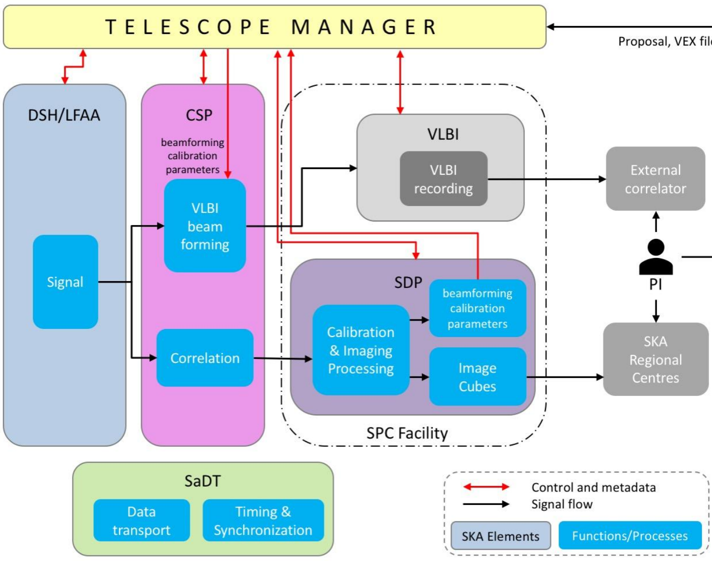

Figure 1. VLBI Observing mode in the SKA1 Observatory

This document shall comply with the SKA1 Interface Management Plan [AD2].

1.4 VLBI Element Overview

The VLBI Element provides the buffering and streaming capability to send SKA VLBI data to an external VLBI correlator and all necessary interfaces for scheduling and conducting the VLBI observations. It is composed by the following sub-elements:

- VLBI Terminal containing the VLBI VDIF recorders.
- VLBI proposal and VEX 2.0 file parser script to generate SKA1 scheduling blocks.
- VLBI Terminal Local Monitoring and Control (LMC).

The VLBI Terminal will be a third-party equipment, provided by an external VLBI Consortium. Its main function will be the recording of the SKA1 VLBI beam data. To allow easy access from the external VLBI Consortium to the VLBI equipment and to not to imposed additional burden in the EMC/EMI control management in the telescopes sites, it will be installed at the Science Processing Centre (SPC) facility. The architecture presented here will allow standard recording (buffer/playback) and e-VLBI mode (real-time external correlation), independently and simultaneously. Expected latencies with the external correlator are about 330 ms, that is the currently experienced latency from New Zealand to The Netherlands.

The VLBI Terminal will be comprised of a COTS (Commercial Off-The-Shelf) general purpose Linux server, a White Box 100GE Ethernet Switch and one or more VLBI VDIF COTS recorders (Figure 2). The number of VDIF recorders depends on the required recording data rate, with the aim to support

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a maximum of 400 Gbps for SKA1-MID and 100 Gpbs for SKA1-LOW imposed by the agreed interfaces. The solution presented here assumes for first light one VDIF recorder for LOW and two VDIF recorders for MID (with at least 32 Gbps capability each) and allows incremental upgrades during the duration of the SKA project.

The general purpose Linux server will implement an LMC within a Tango framework described in the TM to VLBI ICD (RD). The LMC will be responsible for Monitor and Control purposes of the VLBI Terminal by the SKA1 Telescope Manager and for subscription to the appropriate metadata for generation of an observing experiment log required by the External correlator. The server will implement a translator for jive5ab commands and use a generic translator for the Linux server and the Ethernet switch. Proper configuration of the VLBI Tango Alarm handler, logger device, archiver device, metadata client, etc. will be performed during commissioning in accordance with rules adopted by the SKA1 Observatory. The LMC hardware equipment will be selected to have internally redundant components such as power supplies, cooling fans and disk drives (RAID configuration). These internal components contain mechanical parts that wear out over time and that need to be replaceable without affecting the equipment availability. The exact LMC COTS equipment will be selected during construction Phase of SKA1. Table 1 lists a candidate for the Linux server.

The White Box 100GE Ethernet Switch will provide communication with the SKA1 Observatory and the outside world to send the VLBI data to the External correlator and allow access to the Terminal from authorised maintainers. In particular the switch provides communication with the SKA1 Non-Science Data Network (NSDN) for Monitor and Control tasks. The switch will also receive the VLBI VDIF beam data packets, in the specific VDIF format to be used by SKA, and either send them directly to the External correlator in real-time for e-VLBI observing mode or stream them to the VDIF recorders. The Ethernet Switch supported data rate has been chosen to be compatible with the SKA1 NDSN network design and the transport of science data from the Correlator to the rest of the SKA1 Elements. Table 1 lists several candidates for the ethernet switch.

The VLBI VDIF recorders selected for this design are FlexBuff type recorders but other types of compatible VDIF recorders may be used in conjunction or alternatively (e.g. Mark 6 Haystack recorders or NAOJ OCTAVE-families). A FlexBuff is a COTS machine that can record data streams from a telescope and simultaneously stream it for correlation using the jive5ab control application. This combination provides an alternative solution to support e-VLBI observing mode, allowing rewriting of the VDIF packets destinations. Data rates up to 32Gbps have already been verified to be supported by the FlexBuff architecture. The hardware of the FlexBuff is not fixed to specific components, but is built following a general specification as outlined in the *Hardware design document for simultaneous I/O storage elements* [RD11]. Table 1 list the hardware components of a 32Gbps FlexBuff system based on the Onsala EVN station's production system. A FlexBuff system based on solid-state drives (SSD) will be most probably used for SKA1.

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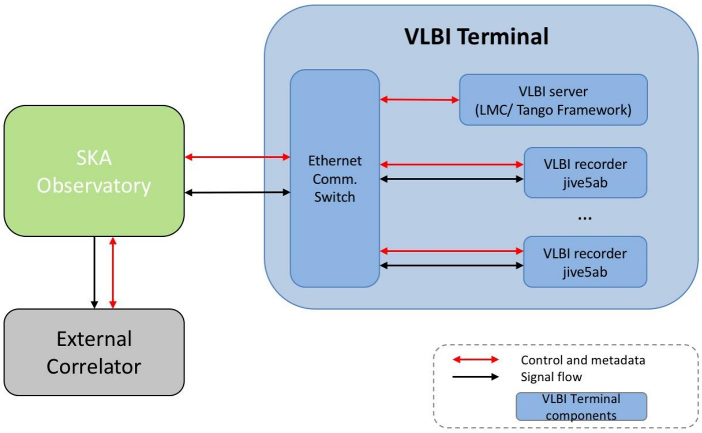

Figure 2. VLBI Terminal schematics

The VLBI equipment will be assembled into 42U 19” racks (one for LOW and two for MID to allow for upgrades) with dimensions 600mm wide and 1070mm deep. All VLBI equipment component will be standard COTS 19” based servers and switches. The weight of each component does not exceed 23 Kg, apart from the FlexBuff recorder that weighs approximately 43 Kg. Each Component will be connected to the rack safety earth connection point. Each rack contains two PDUs, mounted one each side of the back at the rack. Each PDU is plugged into a 3-phase outlet provided by SPC INFRA and each PDU presents banks of 10 outlets for each phase. Each component has dual PSUs (230VAC 50Hz IEC 60320 C13 or C19 power connectors), with one PSU plugged into each PDU. Total power consumption of all VLBI equipment is less than 2.5kW for LOW (assuming 1 FlexBuff of 1280W, Ethernet switch of 550W and server of 550W) and less than 4kW for MID (assuming 2 FlexBuffs of 1280W, Ethernet switch of 550W and server of 550W). The hosting rack provides air cooling interface for VLBI equipment. The maximum VLBI equipment thermal load will not exceed 4kW. VLBI equipment provides mounting guides and location pins on equipment where applicable to facilitate maintenance. The labelling of modules will be in accordance with the SKA1 standards, such that it is readable when the module is removed or installed in its intended operating environment.

<table>
<tr><th>PBS ID</th><th>Name</th></tr>
<tr><td>TBD.002</td><td>19" 1U rack-mount CPU server, air-cooled</td></tr>
<tr><td colspan="2">Rack-mount CPU server platform for running VLBI.LMC Control software.
• COTS Linux server (e.g. Dell PowerEdge R430 https://i.dell.com/sites/doccontent/shared-content/data-sheets/en/Documents/Dell-PowerEdge-R430-Spec-Sheet.pdf).
• Server configured with redundant PSUs, disk drives and cooling fans.
• A different suitable COTS server may be selected during construction.
• Dual 100 GbE NICs required for connectivity with VLBI Control Ethernet Switch.</td></tr>
</table>

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TBD.003	19" 1U rack-mount L2/L3 32-port 100G Ethernet switch, fiber
Rack-mount VLBI Control Ethernet Switch. • 100 GbE Ethernet switch (e.g. FS.COM N8500-32C https://www.fs.com/file/datasheet/n8500-32c-100g-switch-datasheet.pdf or Dell Networking S6100-ON Switch https://www.dell.com/learn/us/en/08/shared-content~data-sheets~en/documents~dell-networking-s6100-on-specsheet.pdf). • Switch configured with 12x100GbE (QSFP) ports, dual PSUs, cooling fans. • A different suitable White Box switch may be selected during construction. • VLBI Ethernet Switch MID provides connectivity between: o 1 x VLBI LMC servers (2x100 GbE optical). o 2 x VLBI recorders (at least 2x100 GbE optical). o SDP Ingress Ethernet Switch (4x100 GbE optical). o SaDT SPC Core router (1x100 GbE optical). o SPC External router (1x100 GbE optical). • VLBI Ethernet Switch LOW provides connectivity between: o 1 x VLBI LMC servers (2x100 GbE optical). o 1 x VLBI recorders (1x100 GbE optical). o SaDT Muxponder (1x100 GbE optical). o SaDT SPC Core router (1x100 GbE optical). o SPC External router (1x100 GbE optical).	
TBD.004	**19" 4U rack-mount FlexBuff Recorder, air-cooled**
Rack-mount VLBI VDIF FlexBuff Recorder 32Gbps. • 8-core CPU (Xeon E5-2760). • 192 GB RAM. • Single port 100 GbE NICs. • 54 x 6TB SATA hard disks (324 TB). • Dual-port Supermicro JBOD chassis (847E16-R1K28JBOD) http://www.supermicro.com/products/chassis/4U/847/SC847E16-R1K28JBOD • Server configured with redundant PSUs and cooling fans. • A different suitable FlexBuff Recorder may be selected during construction, most probably based on SSD technology.	

Table 1. VLBI Equipment description

1.4.1 Supported data rates and buffer size

The number of VDIF recorders required depends on their capability and the required sustained recording data rate, with the aim to support a maximum 400 Gbps (320 Gbps effective) for SKA1-MID and 100 Gpbs (80 Gbps effective) for SKA1-LOW, limit imposed by the data lines initially planned from the SKA1 telescopes to the VLBI terminal.

The SKA1 data rates greatly varies depending on the configuration, number of VLBI beams and number of sub-arrays (Table 2).

For example, for SKA1-MID up to a total of 520 VLBI beams of 200 MHz bandwidth (per polarisation) can be formed among 16 different sub-arrays, with a resulting total maximum data rate of 812.5 Gbps, with 2-bit digitisation and Nyquist sampling. For each sub-array the maximum number of VLBI beams with 200 MHz bandwidth is 52, producing a data rate of 81.25 Gbps per sub-array. This is equivalent to 4 dual polarisation VLBI beams with 2.5 GHz bandwidth per polarisation. Processing resources allow to produce simultaneously VLBI beams for other sub-arrays. In case of four sub-arrays with four 2.5 GHz VLBI beams the data rate is 312.5 Gbps, achieving the maximum allowed by the data lines planned with the VLBI terminal. MID provides up to 16-bit digitisation

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For a MID conservative scenario with 16 VLBI beams in a sub-array with 512 MHz bandwidth per polarisation, the data rate is 64 Gbps. Assuming a FlexBuff recorder with 32 Gbps capability, two units will be enough to support this data rate.

For SKA1-LOW the maximum bandwidth per VLBI beam is limited to 256 MHz per polarisation, with a maximum of 4 VLBI beams produced from all sub-arrays (possibly increasing to 16 beams if Pulsar Timing beams are not used). For 2-bit and Nyquist sampling the data rate is 8 Gbps for 4 beams and 32 Gbps for 16 beams. But LOW allows oversampling (2xNyquist) and up to 8-bit digitisation, increasing these data rates. Assuming a FlexBuff recorder with 32 Gbps capability, one unit will be able to support 16 VLBI beams with 2-bit and Nyquist sampling.

With respect to the buffer size, the European VLBI Network has the requirement to be able to support a whole EVN observing session at 2Gbps standard recording with one FlexBuff buffer capacity. This means 500 TB in total, 250 TB for the local FlexBuff and 250 TB for the FlexBuff unit placed in the correlator. The assumption is that the SKA will participate in the Global VLBI observations that represents approximately a 30% of the total time observed by the EVN in every session. Therefore for 32 Gbps data rates it will be necessary 1200 TB buffer size per FlexBuff unit.

SKA1-MID						
#subarray	**#VLBI beams**	**Bandwidth** (per pol, MHz)	**Digitisation**	**Sampling**	**Data rate** (Gbps)	**Buffer size** (1h, TB)
1	4	256	2	Nyquist	8	3.5
1	4	512	2	Nyquist	16	7
2	4	512	2	Nyquist	32	14
1	4	2500	2	Nyquist	78.12	34
1	16	512	2	Nyquist	64	28
1	52	200	2	Nyquist	81.25	35.7
10	52	200	2	Nyquist	812.5	357
SKA1-LOW						
#subarray	**#VLBI beams**	**Bandwidth** (per pol, MHz)	**Digitisation**	**Sampling**	**Data rate** (Gbps)	**Buffer size** (1h, TB)
1	4	256	2	Nyquist	8	3.5
1	16	256	2	Nyquist	32	14
1	16	256	8	Nyquist	128	56.3

Table 2. VLBI data rates examples for SKA1-MID and LOW. Buffer size calculated for 1h continuous recording.

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1.4.2 Jive5ab control application

Jive5ab is open source software to control the MIT Haystack series of VLBI data recorders (Mark 5A, 5B, 5C and Mark 6) and FlexBuff type recorders that supports more functionalities than the MIT Haystack control software. It accepts incoming TCP/IPv4 connections over which VSI-S formatted commands [AD8] are received and replies sent back. The software allows e-VLBI functionality on all systems, with simultaneous recording to a file. It supports channel dropping to compress the data stream allowing e.g. a 1024 Mbps observation transfer over a 1Gbps ethernet link (=1000Mbps) with 96% sensitivity. It also supports Corner Turning for bringing down the real-time data rate using VDIF legacy headers, distribute one incoming data stream over multiple destinations or convert any of the supported data formats into VDIF format.

Refer to the jive5ab command set version 1.10 [AD6] for a description of the available commands. A translator into jive5ab will be developed for the Tango VLBI LMC for proper control of the VLBI recorders by TM. Table 3 shows a high level description of the VLBI Master Device commands and the correspondence into generic jive5ab commands for a standard recording observation. The translator will properly handle all the different jive5ab commands, parameters, and recording/transfer modes.

Name	Input Type	Input Args	Output Type	Display Level	Allowed in states	Description
Init	None	N/A	DevVoid	OPERATOR	STANDBY ON	Triggers transition to the INIT state: **VLBI Terminal power on.**
Standby	None	N/A	DevVoid	OPERATOR	ON	Triggers transition to the STANDBY state: **Stops jive5ab application (if running).**
On	None	N/A	DevVoid	OPERATOR	STANDBY	Triggers transition to the ON state: **Starts jive5ab application and configures it.**
StartCapture	None	N/A	DevVoid	OPERATOR	ON	Command to start capturing VLBI beams: **Sends jive5ab record=on command.**
StopCapture	None	N/A	DevVoid	OPERATOR	ON	Command to stop capturing VLBI beams: **Sends jive5ab record=off command.**

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StartTransfer	None	N/A	DevVoid	OPERATOR	ON	Command to start transferring data: **Sends jive5ab disk2net command.**
StopTransfer	None	N/A	DevVoid	OPERATOR	ON	Command to stop transferring data: **Sends jive5ab disk2net command.**

Table 3. VLBI Master Device Commands and correspondence into jive5ab commands.

2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

AD[1] SKA Project Safety Management Plan, SKA-TEL-SKO-0000740, Rev 01

AD[2] SKA1 Interface Management Plan, SKA-TEL-SKO-0000025, Rev 02

AD[3] SKA Phase 1 System (Level 1) Requirements Specification, SKA-TEL-SKO-0000008, Rev 11

AD[4] VLBI Data Interchange Format (VDIF) Specification, Release 1.1.1, June 2014, http://vlbi.org/vdif/docs/VDIF_specification_Release_1.1.1.pdf

AD[5] VTP: VDIF Transport Protocol, Release 1.0.0, 30 October 2013, http://vlbi.org/docs/2013.10.30_VTP_rev_1.0.pdf

AD[6] Jive5ab command set 1.10 http://www.jive.nl/~verkout/evlbi/jive5ab-documentation-1.10.pdf

AD[7] VEX 2.0 file format, https://safe.nrao.edu/wiki/bin/view/VLBA/Vex2doc

AD[8] VSI-S specification, VLBI Standard Interface - Software, https://vlbi.org/vsi/docs/2003_02_13_vsi-s_final_rev_1.pdf

2.2 Reference documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

RD[1] CSP MID to VLBI Interface Control Document, 300-000000-032, Rev 1

RD[2] CSP LOW to VLBI Interface Control Document, 100-000000-032, Rev 1

RD[3] TM to VLBI Interface Control Document, SKA-TEL-SKO-0000932, Rev 1

RD[4] SADT MID to VLBI Interface Control Document, 300-000000-xxx, draft

RD[5] SADT LOW to VLBI Interface Control Document, 100-000000-xxx, draft

RD[6] SDP MID to VLBI Interface Control Document, 300-000000-xxx, draft

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RD[7] SADT MID to CSP Interface Control Document, 300-000000-023, Rev 3

RD[8] SADT LOW to CSP Interface Control Document, 100-000000-023, Rev 3

RD[9] SDP MID to CSP Interface Control Document, 300-000000-002, Rev 3

RD[10] SADT MID to SDP Interface Control Document, 300-000000-025, Rev 4

RD[11] Hardware design document for simultaneous I/O storage elements, NEXPReS Deliverable D8.2, http://www.jive.nl/nexpres/lib/exe/fetch.php?media=nexpres:2011-02-28_wp8-d8.2.pdf

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3 INTERFACE DEFINITION

This External Interface Control Document (EICD) describes the interfaces between the SKA and the VLBI Element for both SKA1-LOW and SKA1-MID Telescopes (Figure 3).

The list of interfaces is the following:

- External VLBI interface with the SKA Observatory (this EICD). This interface describes the VLBI Element, the particular VDIF data exchange format to be used by the CSP Correlator Beamformer, the information contained in the VEX 2.0 file provided by the PI to generate scheduling blocks (SBs), the jive5ab translator, etc.

- Interface with the SPC facility Infrastructure: The detailed interface is not part of this delivery but will be specified in the SKA1 Observatory agreement for third party equipment to be installed at the SPC facilities. Anyway, the details of necessary space, rack, power, cooling, etc. are specified in the External VLBI Interface (this EICD). This agreement will also provide Internet access to the VLBI Terminal for streaming of VLBI data to the external correlator, detailing the connections to the SPC external communications router.

- Interface with the Signal and Data Transport (SaDT) Element [RD4], [RD5]: For both telescopes SaDT will interface with the VLBI Terminal to provide connection to the Non-Science Data Network (NSDN) for monitor and control of the terminal by the Telescope Manager (TM) Element and typical network infrastructure services (e.g. NTP). SaDT LOW [RD5] will also interface with the VLBI Element to provide the spigot for real-time streaming of the VLBI beams data from the Correlator Beamformer to the VLBI recorders via a Muxponder. For the MID telescope the data spigot is provided by the SDP Element.

- Interface with the Central Signal Processor (CSP) Element [RD1], [RD2]: interface for each telescope detailing the VLBI beamformer capabilities and products, specifically numbers of VLBI beams, number of channels per beam, bandwidth and central frequency, digitization and sampling, etc.

- Interface with the Telescope Manager (TM) Element [RD3]: this interface describes the Monitor and Control of the VLBI Terminal, e.g. for set-up and control of the VLBI recorders during the VLBI experiments, monitoring of the VLBI Terminal (e.g. alarms, logging, etc.) and subscription to metadata. For these functions the VLBI Element will implement a Local Monitoring and Control sub-element (VLBI.LMC) using the TANGO control system framework, harmonised with the SKA1 Elements.

- Interface with the Science Data Processor (SDP) Element [RD6]: this interface provides the data spigot from the MID Correlator and Beamformer (for the MID telescope only) to the VLBI recorders via the SDP Ingress Ethernet Switch.

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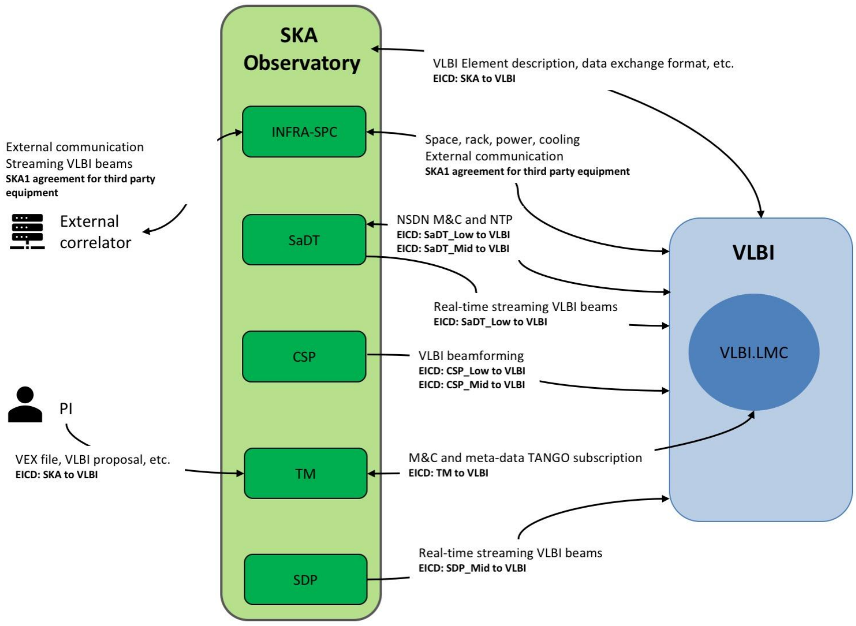

Figure 3. SKA to VLBI Interface, including interfaces with the different SKA Elements

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3.1 Interface Identification

Unique identifiers are prescribed for each of the interfaces pertinent to the SKA-VLBI ICD; the methodology imposed shall permit the immediate identification of any given interface, and following the underlying logic:

I.S1T.xxxx_yyyy.nnn.ccc

Where periods are used as separators and digits are defined as follows:

I	Defines the item as an interface
S	Defines that the item pertains to the SKA Project
1	Defines the item as being current at Phase 1†
T	Defines whether the item pertains to the Telescope (T), MID (M) or LOW (L)
xxxx	Defines the interfacing element 1 (lead)‡
yyyy	Defines interfacing element 2 (non-lead)‡
nnn	A unique number string between 001 and 999
ccc	Text describing the data

Notes:

† Subsequent numbering/lettering to be used as appropriate for progressive project phases.

‡ A list of suitable element acronyms are tabulated (Table 4):

Interface No.	SKA Product ID	VLBI Product ID	Interface Description
I.S1L.SKA_VLBI.001	**SKA1-LOW** 100-000000	**VLBI Terminal** CIN (TBD.001)	Data exchange format
I.S1M.SKA_VLBI.001	**SKA1-MID** 300-000000	**VLBI Terminal** CIN (TBD.001)	Data exchange format

Table 4. SKA-VLBI Interface Identification

For example:

I.S1L.SKA_VLBI.001

Defines an interface (I) belonging to the SKA project (S), current under phase 1 (1), specifically to SKA1-LOW (L), where SKA element is lead and interfaces with the VLBI Element (VLBI), and the specific interface is number 001.

In this ICD each interface will be identified, its constituents clearly and qualitatively described and fundamental requirements and specifications shall be disclosed. And finally, be supplemented by the element's respective Product Name and Configuration Item (CI) number, in the following manner:

- **Signal and Data Transport** – 105-000000
- **CSP Correlator and Beamformer** – 111-000000

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3.1.1 I.S1L.SKA_VLBI.001

Interface is between the **SKA1-LOW** and **VLBI Element**, and facilitates data exchange relating to "VLBI" science data which has been processed by the Central Signal Processor (CSP). It also facilitates data exchange relating to non-science data, typical network infrastructure services (e.g. NTP), and monitor and control functions to Telescope Manager.

3.1.2 I.S1M.SKA_VLBI.001

Interface is between the **SKA1-MID** and **VLBI Element**, and facilitates data exchange relating to "VLBI" science data which has been processed by the Central Signal Processor (CSP). It also facilitates data exchange relating to non-science data, typical network infrastructure services (e.g. NTP), and monitor and control functions to Telescope Manager.

3.2 Interface Topology

The interfaces described in this document are between the SKA1 Observatory and the external VLBI Terminal. Figures 4 and 5 show the VLBI LOW and MID VLBI interfaces topology. Please note that the interfaces are different for each telescope.

The basic breakdown of VLBI data transport responsibilities for SKA1-LOW telescope is as follows (Figure 4):

1) CSP_LOW Element shall provide 1 x 100GE dedicated fibre output for VLBI beamformed data [RD8]. VLBI data shall conform the data exchange format described in this ICD.
2) SaDT shall be responsible for transport of the CSP_LOW VLBI output data from the CSP to an SaDT Muxponder at the SPC Facility, through a 1 x 100GE dedicated fibre link [RD8].
3) SaDT shall provide 1 x 100GE fibre output at the SaDT Muxponder at the SPC Facility [RD5].
4) The external VLBI equipment stakeholders shall be responsible for the 1 x 100GE data link from the SaDT Muxponder to the location of the external VLBI equipment at the SPC. This location shall be described in the SKA1 Observatory agreement for third party equipment to be installed at the SPC facilities.
5) Internet connection to the external correlator shall be described in the third party equipment agreements.

The basic breakdown of VLBI data transport responsibilities for SKA1-MID telescope is as follows (Figure 5):

1) CSP shall provide 80 x 100GE shared fibre outputs for visibility and VLBI beamformed data which shall connect to SDP Ingress Ethernet switch [RD9]. VLBI data shall conform the data exchange format described in this ICD.
2) SaDT shall be responsible for transport of the CSP_Mid VLBI output data from the CSP to the SDP Ingress Ethernet switch [RD7, RD10].
3) SDP shall be responsible for providing 4x100GE ports at the SDP Ingress Ethernet switch (via a firewall) [RD6].
4) The external VLBI equipment stakeholders shall be responsible for the 4x100 GE data links from the SDP Ingress Ethernet switch to the location of the external VLBI equipment at the SPC. This location shall be described in the SKA1 Observatory agreement for third party equipment to be installed at the SPC facilities.

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5) Internet connection to the external correlator shall be described in the third party equipment agreements.

The basic breakdown of VLBI monitor and control responsibilities for SKA1-COMMON telescope is as follows:

1) SaDT shall be responsible for the connection of the VLBI terminal to the NSDN Network for Monitor and Control tasks, and subscription to metadata, and NTP services. For this purpose, SaDT shall provide 1x100GE port at the SaDT SPC core routers (via a firewall) [RD4, RD5].
2) The external VLBI equipment stakeholders shall be responsible for the 1x100GE data link from the SaDT SPC core routers to the location of the external VLBI equipment. This location shall be described in the SKA1 Observatory agreement for third party equipment to be installed at the SPC facilities.
3) TM shall process the VEX file and additionally supplied information into valid Scheduling Blocks [RD3].
4) TM shall monitor and control the VLBI Terminal via a Tango LMC [RD3].

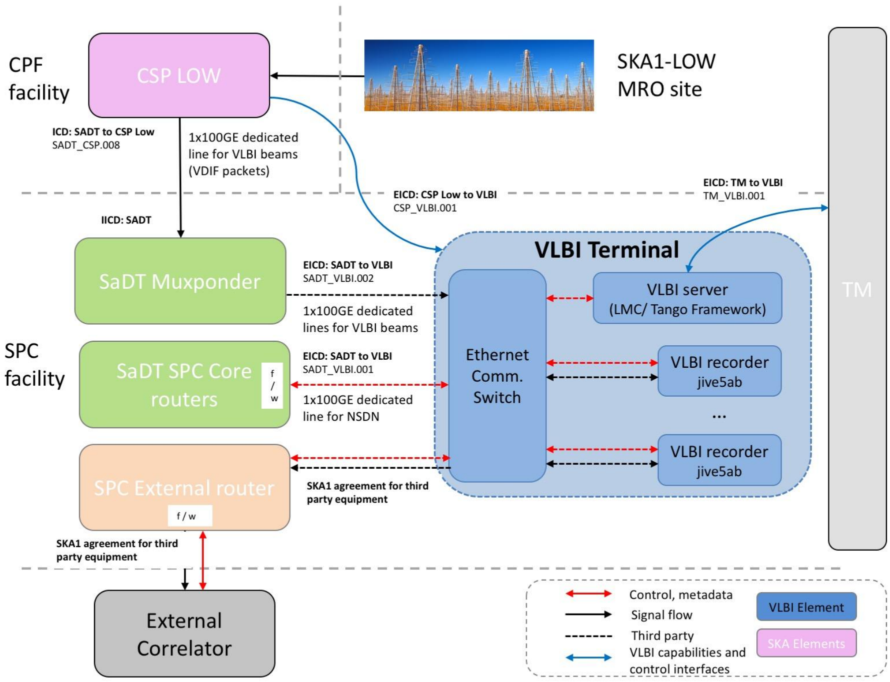

Figure 4. VLBI LOW ICD Topology

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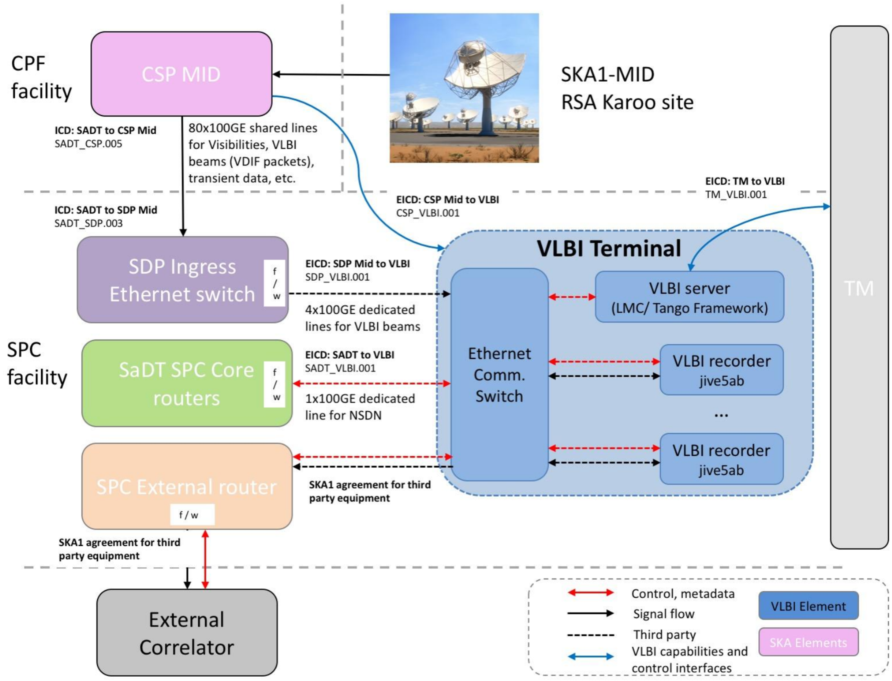

Figure 5. VLBI MID ICD Topology

3.3 Summary of standards rationales

The list of standards employed by this interface is summarized in the Table 5 below:

Interface Standards	Rationale
RFC 768 User Datagram Protocol	Common protocol used to network with computers and servers. UDP is light weight, a small transport layer designed on top of IP. UDP is suitable for applications that need fast, efficient transmission.
RFC 792 Internet Control Message Protocol	Common protocol used to report errors in the processing of datagrams; e.g. the echo request and echo reply functionality used by programs like "ping" provide simple and useful link diagnostic capability. ICMP is an integral part of IP and must be implemented by every IP module.
VLBI Data Interchange Format (VDIF) Specification	This is a standardized transport-independent VLBI data-interchange format that is suitable for all types of VLBI data transfer, including real-time and near-real-time e-VLBI, as well as disk-file storage [RD2]
VDIF Transport Protocol (VTP)	UDP over Ethernet VDIF Transport Protocol [RD3]
VEX 2.0	**V**lbi **EX**periment file format for complete description of the VLBI experiment, including scheduling, data-taking and correlation [RD]

Table 5. Summary of Standards

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3.4 VDIF data packet format

The output of the SKA1 telescopes shall be compatible with the VLBI Data Interface Specification (VDIF) RD[2]. This is a standardized transport-independent VLBI data-interchange format that is suitable for all types of VLBI data transfer, including real-time and near-real-time e-VLBI, as well as disk-file storage. It supports data rates up to at least ~100 Gbps and observations over leap seconds and year boundaries.

The VDIF format specification allows data to be stored in VDIF data frames, each containing a short self-identifying Data Frame Header, followed by a Data Array (containing the actual samples). The length of a Data Frame may be chosen by the user to best match the transport protocol, with the restriction that it is a multiple of 8 bytes and the number of VDIF data frames be integer per second. Check Table 6 for several data frame examples for a 200 MHz bandwidth beam channel.

Channel Bandwidth (MHz)	Bits/sample	Data rate (Mbps)	Frame Size (Bytes)	Data Frames/Sec
200	2	800	1280	625000
200	2	800	1600	500000
200	2	800	2000	400000
200	2	800	3200	250000
200	2	800	4000	200000
200	2	800	5000	160000
200	2	800	6400	125000
200	2	800	8000	100000

Table 6. VDIF data frame lengths examples for 200 MHz beam channels.

Each Data Frame consist of either a single channel or multiple channels. For the particular case of the SKA-VLBI capability it is preferable that the VDIF Data Frames consist on single beam-channel real data (only one polarisation). In the VDIF concept, each time-series of Data Frames from the same set of channels is known as a 'Data Thread', where each of the Data Frames within the Data Thread is identified by a 'Thread ID' embedded in the Data Frame Header. For actual transmission over the network, or for storage on a disk file, the set of Data Threads that comprise the data set can be merged into a single serial 'Data Stream' or can be kept separated in individual 'Data Streams' for each Data Thread. This decision depends on the links capacity and on the FlexBuff recorder capability. Therefore, for SKA there could be a Data Stream consisting of multiple single channel

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Data Threads, one for each VLBI beam-channel and polarisation, or several parallel Data Streams each consisting of one Data Thread, each Data Thread with single VLBI beam-channel data.

The Data Frame Header has a standard 32-byte length (Figure 6). Bit 30 must be always set to 0.

Bit 31 (MSB) — Byte 3 — Byte 2 — Byte 1 — Byte 0 — Bit 0 (LSB)

Word 0	I_1	L_1	Seconds from reference epoch$_{30}$	
Word 1	Un-assigned$_2$	Ref Epoch$_6$	Data Frame # within second$_{24}$	
Word 2	V_3	log$_2$(#chns)$_5$	Data Frame length (units of 8 bytes)$_{24}$	
Word 3	C_1	bits/sample-1$_5$	Thread ID$_{10}$	Station ID$_{16}$
Word 4	EDV$_8$		Extended User Data$_{24}$	
Word 5	Extended User Data$_{32}$			
Word 6	Extended User Data$_{32}$			
Word 7	Extended User Data$_{32}$			

Figure 6. VDIF Data Frame Header format; subscripts are field lengths in bits; byte #s indicate relative byte address within 32-bit word (little endian format)

For the particular case of the SKA, a telescope with multi-beam capability, it is necessary to properly identify the subarrays and their VLBI beams in the VDIF headers. A proposed solution is to set the station ID to a standard two-letter code (e.g. “SK”) and allocate an EDV for SKA that would contain information about the subarray and the VLBI beam that is producing the sample. This decision needs to be approved by the VDIF Committee, and the EDV would need to be documented (TBD.005).

For more information on the different header fields, see the VLBI Data Interchange Format (VDIF) Specification [RD 2]. Bit arrangement is Little Endian, "reading" the bits from right-to-left.

For Data Arrays carrying single-channel data, as it is recommended for SKA, the Data Array format for 2bits/sample is shown in Figure 7 as an example; other values of bits/sample are formatted similarly but are not illustrated here, refer to the VLBI Data Interchange Format (VDIF) Specification [RD 2].

Bit 31 — Bit 0

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

Figure 7. Real 2 bits/sample data-word format

Channel bits are sampled using the "Offset Binary" encoding scheme. For the common 2-bit scheme, then, if a voltage threshold level is set at L, (L > 0) the measured voltages shall be encoded as in Table 7.

2-bit encoding	Voltage v
11	L < v
10	0 ≤ v < L
01	-L, ≤ v < 0
00	v < -L,

Table 7. 2 bit "Offset Binary" Data Encoding

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3.5 VDIF data transport protocol: VTP

Data packets shall be streamed as UDP/IPv4 over Ethernet in accordance with the VDIF Transport Protocol RD[3]. UDP is an unreliable packet streams and as such needs a way of determining packet drops or reordering. While the VDIF headers contain enough information to unambiguously reorder frames and detect missing data, it is important to distinguish packets dropped by the network from those dropped at the sending side (e.g. in burst mode or when the source deliberately drops frames to reduce the data rate).

Each UDP datagram (or UDP Payload) consists of a 64-bit (8 byte) unsigned integer packet sequence number (PSN) in little-endian byte order, followed by a single VDIF data frame. The sequence numbers must be kept per sender for each unique destination tuple (IPv4 address, UDP port number). The sequence number for a destination shall be incremented by one for each frame sent to that destination. There should always be a single VDIF frame per UDP datagram. VDIF frames should not span multiple datagrams nor should a datagram contain multiple VDIF frames.

A VTP/UDP source should be mindful of the following:

1. It is important to properly fill in the Ethernet, IPv4 and UDP headers with correct source and destination ports, IP addresses, and MAC addresses. The stream port number should be negotiated between source and sink. Standard port numbers starting at 29000 should be used as a default. These values will be attached to the VLBI Project and/or extracted from the TM EDA (Engineering Data Archive) database and communicated to CBF sub-element for configuration via Scheduling Blocks.

2. UDP allows datagrams up to 64kB, which is larger than Ethernet frame size. VTP/UDP allows VDIF frames that are fragmented over multiple Ethernet frames (but within a single UDP datagram). However, such usage is discouraged and generally a VTP/UDP source should ensure the UDP datagram fits within the underlying Ethernet MTU.

3. It is allowed to skip performing the UDP checksum by setting the value to 0 in the UDP header for that field.

4. The sequence number for a particular destination need not start from 0

The UDP Packet format is shown in Figure 8, with details on the standard header and trailer format of a generic UDP packet (Figure 9), generic IP header (Figure 10) and generic UDP header format (Figure 11). The appropriate VDIF packets destinations will be added by the SKA1 correlators for standard recording or e-VLBI mode.

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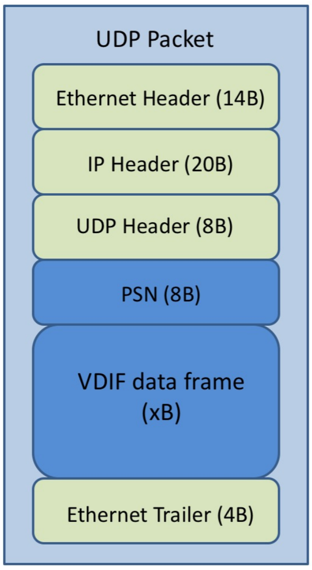

Figure 8. UDP Packet Format with VDIF data

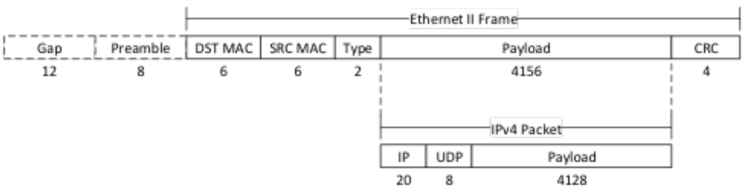

Figure 9. Header and Trailer Format of Generic UDP Packet

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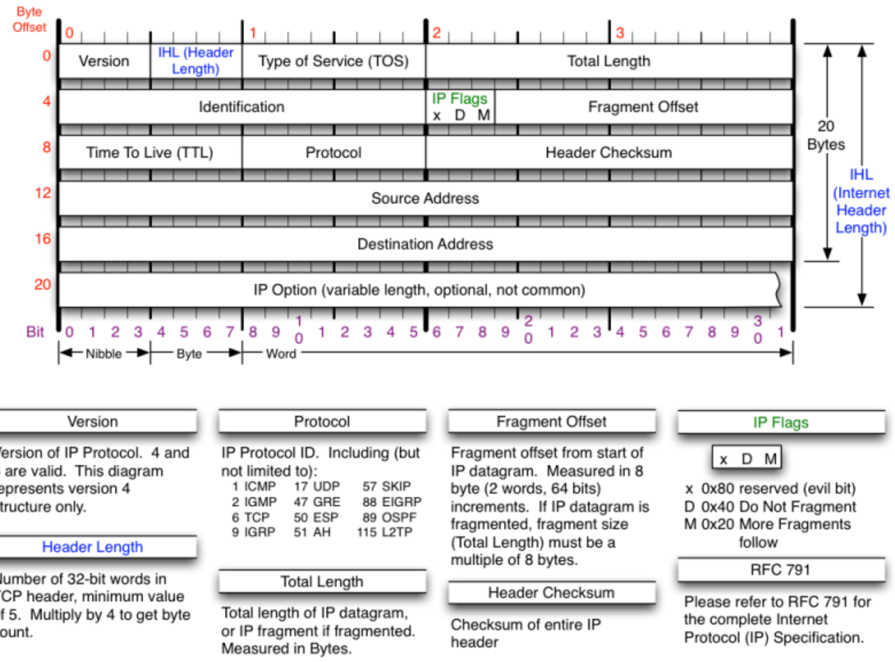

Figure 10. Generic IP Header Format

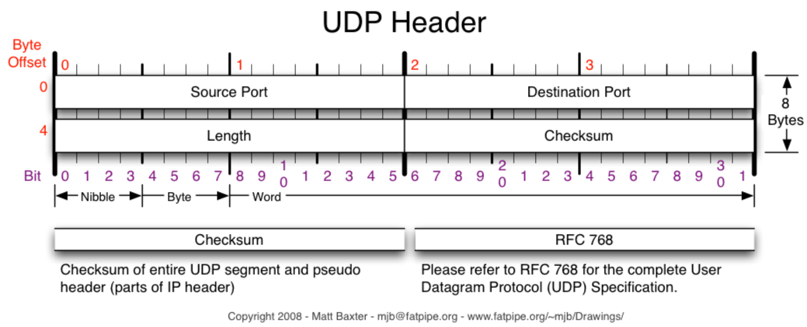

Figure 11. Generic UDP Header Format

3.6 VEX 2.0 file format

The VLBI experiment schedule file is the defined interface between the VLBI Principal Investigator and the SKA1 Observatory. The schedule file consists of a single self-contained file in VEX format. In-depth description and definition of the 'VEX-file' format including scheduling, data taking, and correlation is documented on the VLBI website: http://www.vlbi.org/vex/. The website describes the VEX-file format and the elements of primitive $blocks such as $ANTENNA, $SITE, and $PROCEDURES that have been created by VLBI developers in collaboration with the developers of the VEX format. This is available to the VLBI PIs via this interface in order to facilitate scheduling of VLBI experiments

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in the SKA. The Global VLBI Networks require the radio observatories to keep up-to-date EVN status tables and SCHED catalogue information.

The schedule file name is an arbitrary string of alphanumeric characters, followed by a dot (".") character (ASCII value 37), and then appended with either the three-character extension "skd" or "vex". The use of "skd" or "vex" extension depends on the VLBI scheduling software used by the PI, however the contents of the file must follow the VEX v1.5 format. By the time SKA1 is operational VEX 2.0 standard will be adopted [RD]. VEX2 is an update of the original VEX (VEX1), developed to more logically accommodate the sampling-before-channelization (aka `IF sampling') paradigm represented by modern digital-backend (DBE) systems, as well as updates that allow better equipment description, setup and signal connections. It also allows multi-beam telescopes and scan intents definition for e.g. beamforming, suitable for SKA1 telescopes description.

The schedule file is not station specific and includes information for all stations in the VLBI network participating in the scheduled VLBI observation.

3.6.1 File Format Composition

Files in VEX format are composed of organizational units called $blocks. There are three types of $blocks:

1. Primitive $block(s) that define set of parameters.
2. High level $block(s) which are constructed from references to primitive $blocks and which contain all parameters necessary to specify an experiment.
3. A $SCHED $block which specifies the observation schedule.

Schedule files in VEX format contain the $blocks necessary to generate Scheduling Block (SB) for observation execution. An OSO API shall ingest and parse the VEX files to extract the necessary technical details needed to generate the associated SBs.

Primitive $blocks consist entirely of keyword 'def blocks' which define low-level station, source, and recording parameters. The currently defined primitive $blocks and their use in various stages of the experiment are summarized below (Table 8). High level $blocks contain references to primitive $blocks to configure each participating station (Table 9). The $SCHED block, specifies a detailed time-ordered list of observations, using keyword references to $STATION, $MODE, and $SOURCE 'defs'.

$ANTENNA	Antenna Parameters
$BBC	BBC/IF Assignments
$DATASTREAMS	VDIF Ethernet-based VLBI datastreams description
$FREQ	Channel Frequencies and bandwidths
$IF	IF Bands/Side Bands, 1st LO Frequency, Phase Cal Frequencies
$SCHED	Time-ordered list of observations
$SITE	Antenna Site Details
$SOURCE	Source Name, Positions, etc.

Table 8. VEX Primitive Block Names to be used in SKA Scheduling

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$GLOBAL	Specify global/general information. Only "refs" to primitive-block keywords are permitted.
$STATION	Specify station parameters. Consists of 'def' blocks containing 'refs' to primitive blocks.
$MODE	Specify station-dependent setup parameters that can change between experiments
$EXPER	General experiment information, experimenter contact info, target correlator info, etc. Primarily for bookkeeping.

Table 9. VEX High Level Block Names

4 SAFETY ASPECTS

Safety aspects of interfaces arise from application of the safety provisions of the SKA Project Safety Management Plan [AD1], such as the mandatory Safety Assessment. In addition to the products of the Safety programme, safety critical interfaces shall be highlighted in ICDs as in any other design or operations related documents.

No safety aspects have been identified for this interface, as it specifies a Data Exchange interface which carries no safety-related information.

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5 INTERFACE VERIFICATION

Interface verification occurs at many stages in the integration of the Elements. It is carried out to demonstrate that the design and implementation conform to the ICD, and it will be described in formal procedures. A key distinction is made between verification tests that require the interfacing Element and those that do not (using a simulator or standard test equipment). The ICD shall contain a section on the verification methods to be used to:

1. *Verify the design and implementation of interfacing hardware and software without the interface being made*
2. *Verify the interface for integration and acceptance purposes (involving the interface being made)*

The execution of the first case is the responsibility of the respective interfacing parties.

The SKAO provided template and the SKA Interface Management Plan *(AD[2]) identify the Leading interfacing party as responsible for specifying verification methods and procedures, and for executing them, in the second case above (interface being made). However, in the case of this interface, VLBI equipment will be provided by the party external to SKA, and the CSP Consortium cannot take responsibility for executing verification methods and procedures.*

For each interface specification, the verification method and the level at which the verification will occur must be specified.

To be completed in subsequent release.

6 TBD ITEMS

TBDs are summarised in the table below (Table 10):

Item No.	Description	Owner	Required
TBD.001	VLBI Terminal CIN	SKAO	System CDR
TBD.002	VLBI Terminal Server PBS ID	SKAO	System CDR
TBD.003	VLBI Terminal Ethernet Switch PBS ID	SKAO	System CDR
TBD.004	VLBI Terminal Recorder PBS ID	SKAO	System CDR
TBD.005	Usage of VDIF header field EDV to identify subarrays and VLBI beams	VLBI Consortium/ VDIF Committee	System CDR

Table 10. Summary of TBDs

6.1 Known issues and outstanding items

7 INTERFACE REQUIREMENTS

SADT Req. ID	Requirement

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Table 11. Requirements I.S1L.SKA_VLBI.001

SADT Req. ID	Requirement

Table 12. Requirements I.S1M.SKA_VLBI.001

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ANNEX 2: SKA Consortia to VLBI Interface Control Documents

ANNEX 2.1 LOW Central Signal Processor (CSP) to VLBI ICD

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SKA1_LOW TELESCOPE
INTERFACE CONTROL DOCUMENT
CSP TO VLBI

Document Number 100-000000-032
Document Type .... ICD
Revision 01
CSP Document Number SKA-TEL.CSP.SE-VLBI-ICD-001
Author ....John Bunton
Date 2018-06-26
Document Classification .... UNRESTRICTED
Status .... Released

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W. Turner	CSP IET System Engineer	SKAO	W.Turner
R. Olguin	SaDT System Engineer	SKAO	Rodrigo Olguin M.
Released by:			
J. McMullin	Programme Director	SKAO	J P McMullin 2018-07-04

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DOCUMENT HISTORY

Revision	Date of Issue	Engineering Change Number	Comments
A	2017-12-19	ECP-160040, ECP-170053	First draft as per ECP-170053.
01	2017-12-19		New doc # assignment
	2018-01-05		Updated ICD content based on CSP_Mid to VLBI ICD.
	2018-01-13		Changed author; reference external VLBI ICD; incorporate responses to SKAO comments
	2018-01-15		Incorporated responses to comments from SKAO SaDT System Engineer.
	2018-05-14		Updated interface topology. Included missing aspects of the data exchange specifications. Added total VLBI output data rate calculation. Changed Interface Requirement ID.
	2018-06-18		Incorporated responses to comments from SKAO System Engineers (LOW, SaDT and CSP IET).
	2018 –06-26		First Revision Released

DOCUMENT SOFTWARE

	Package	Version	Filename
Word processor			100-000000-032-01_CSPLow-to-VLBI_ICD
Block diagrams			
Other			

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington, Macclesfield Cheshire SK11 9DL Registered in England & Wales Company Number: 07881918
Website	www.skatelescope.org

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TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF FIGURES

LIST OF TABLES

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LIST OF ABBREVIATIONS

CIN ....Configuration Item (number)
CSP ....Central Signal Processor Element
CSP_Low ....Central Signal Processor in the SKA1_Low Telescope
HMI................................Human-Machine Interface
ICD ....Interface Control Document
OSI ....Open Systems Interconnection
SADT.............................Signal and Data Transport Element
SDP ....Science Data Processor Element
SKA ....Square Kilometre Array
SKAO ....SKA Organization
TBC ....To Be Confirmed
TBD ....To Be Decided
TM ....Telescope Manager
UDP...............................User Datagram Protocol
VDIF ....VLBI Data Interchange Format
VLBI...............................Very Long Baseline Interferometry
VTP ....VDIF Transport Protocol

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1 Introduction

1.1 Scope and purpose

This document defines the interfaces between the SKA1_Low Central Signal Processor (CSP_Low) element and the externally supplied VLBI equipment. The capabilities described are those provided by CSP_Low; this does not guarantee that these full capabilities will be supported by TM and the telescope as a whole at the end of construction. This document should be read in conjunction with the SKA1 External VLBI ICD RD[3], which will contain details about the VLBI terminal, the VDIF data format, required metadata and their format, etc.

The basic breakdown of VLBI data transport responsibilities is as follows:

1) CSP_Low provides a single 100 GE fibre output for VLBI data, independent of visibility data.
2) The SaDT Element is responsible for transport of the CSP_Low VLBI output data from the CSP to the designated place (TBD01) in the Science Processing Centre.
3) The external VLBI equipment stakeholders are responsible for data links from the designated place in the Science Processing Centre to the location of the external VLBI equipment.

This document complies with the SKA Interface Management Plan AD[2].

1.2 Interface Identification

This Interface Control Document (ICD) defines the requirements and implementation details of the interface:

I.S1L.CSP_VLBI.001 "SKA1_Low_Central Signal Processor to VLBI Interface".

[Note: the interface identifier used is I.S1t.xxx_yyy.nnn, where:
S = SKA,
1 = Phase 1,
t = Telescope: L for Low.
Xxx = Interfacing element 1
Yyy = Interfacing element 2
nnn = identification number]

This interface involves the following items of the SKA1-Low Telescope:

1) CSP Correlator and Beamformer (CBF) Low (Configuration Item Number (CIN) 111-000000)
2) External VLBI equipment (Configuration Item Number (CIN) TDB02)

CIN number for VLBI equipment (TBD02) is specified at the SKA1 External VLBI Interface Control Document RD[3].

1.2.1 Interface Requirement Identification

Within the ICD, when only one interface is described, requirements are identified as follows:

R.nnn *[nnn is an identification number]*

If more than one interface is represented in one ICD, then a Unique Interface Requirement Identification Label (UIRIL) is used and defined as follows:

IIC.R.nnn *[IIC=Interface Identification Code, R stands for Requirement, nnn is an identification number]*

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1.3 Applicable and Reference documents

1.3.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

AD[1] SKA Project Safety Management Plan ", SKA-TEL-SKO-0000740, Rev 01

AD[2] SKA1 Interface Management Plan, SKA-TEL-SKO-0000025, Rev 02
AD[3] SKA Phase 1 System (Level 1) Requirements Specification, SKA-TEL-SKO-0000008, Rev 11
AD[4] INTERFACE CONTROL DOCUMENT SADT TO CSP (Low), 100-000000-023, Rev 03
AD[5] VLBI Data Interchange Format (VDIF) Specification, Release 1.1.1, June 2014, http://vlbi.org/vdif/docs/VDIF_specification_Release_1.1.1.pdf
AD[6] VTP: VDIF Transport Protocol, Release 1.0.0, 30 October 2013, http://vlbi.org/docs/2013.10.30_VTP_rev_1.0.pdf

1.3.2 Reference documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

RD[1] SKA CSP Element Requirements Specification (SE-2), SKA-TEL-CSP-0000010, Rev 05

RD[2] SKA1 CSP Low Correlator and Beamformer Sub-element Detailed Design Document (EA-4a), 111-000000-003

RD[3] SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116, to be released

RD[4] INTERFACE CONTROL DOCUMENT CSP Low TO TM, 100-000000-021, Rev 03

1.4 Roles and responsibilities

Table 1-1 shows the roles and responsibilities for the relevant parties.

Table 1-1 : Roles and responsibilities

Role	Organization	Point of contact	Responsibilities
Author	CSP Consortium	CSP_Low.CBF Lead Engineer	Create and maintain this document
Leading party	CSP Consortium	CSP_Low System Engineer	Contribute to, review and approve this document
Approving party	SKAO	CSP IET System Engineer	Contribute to, review and approve this document
Owning party	SKAO	LOW System Engineer	Oversight, approval and release
Reviewer	SaDT Consortium	SaDT Consortium Lead	Review and approve this document
Reviewer	SKAO	SaDT System Engineer	Review and approve this document

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1.5 Interface scope

Table 1-2 lists the classes of interface specification included in this document.

Table 1-2 : Interface class specifications

Interface class	Included in document?
Mechanical	N
Fluid	N
Thermal	N
Electromagnetic	N
Optical	N
Electrical	N
Electronic	N
Electro-optical	N
Data exchange specifications	**Y**
Human-Machine Interface	N

1.6 Interface topology

The interfaces described in this document are between the CSP Element and external VLBI equipment. The SADT Element provides the OSI physical layer (Layer 1) connection between the CSP and the external VLBI equipment. This physical layer consists of 1 x 100GbE fibre optical links from CSP_Low.CBF to the Science Processing Centre (I.S1L.SADT_CSP.008) as described in the SKA Low SADT to CSP ICD (AD[4]).

The following assumptions have been made:

1) The SaDT Element is responsible for transport of the CSP_Low VLBI output data from the CSP to the designated place (TBD01) in the Science Processing Centre.
2) The external VLBI equipment stakeholders are responsible for data links from the Science Processing Centre to the location of the external VLBI equipment. This interface has been defined as I.S1M.SADT_VLBI.001 (TBD03) to be documented in RD[3].

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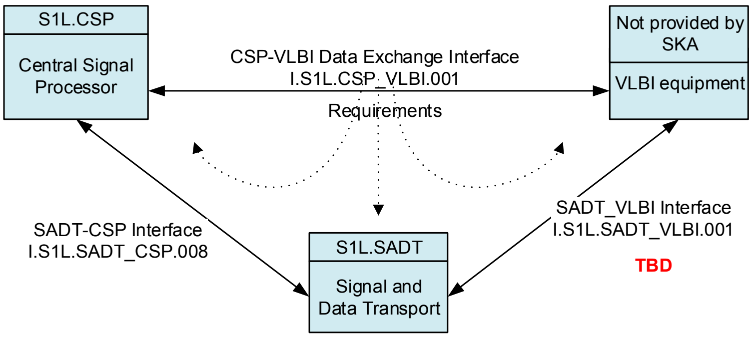
Figure 1-1 Interface Topology



1.7 Summary of standards rationales

CSP_Low transmits the VLBI data using the VDIF format, which is in extensive use by the VLBI community AD[5]. Thus, to provide compatibility of the SKA1 Low VLBI 'station' with existing and planned VLBI equipment, CSP_Low adopts this standard for VLBI beam data output.

1.8 Data packet format

The output of the CSP Element is compatible with the VLBI Data Interface Specification (VDIF) AD[5].

1.9 Data transport protocol

Data packets are streamed as UDP over Ethernet in accordance with the VDIF Transport Protocol AD[6].

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2 Specification Class List and Applicable Standards

2.1 Data Exchange Specifications

CSP_Low implements the following standards:

1) VLBI Data Interchange Format (VDIF) Specification, AD[5].
2) VTP: VDIF Transport Protocol, AD[6].

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3 Test, Diagnostic or Maintenance Features

Any design features provided at the interface exclusively for testing, diagnosis or maintenance procedures, for the interface itself, shall be documented in this section. The presentation of these features shall follow the same logic as that for the main interface.

To be completed in subsequent release (TBD04).

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4 Safety Aspects

Safety aspects of interfaces arise from application of the safety provisions of the SKA Project Safety Management Plan AD[1], such as the mandatory Safety Assessment. In addition to the products of the Safety programme, safety critical interfaces shall be highlighted in ICDs as in any other design or operations related documents.

Safety concerns have not been identified so far. Note that safety concerns related to lasers are addressed by the ICD SADT to CSP, AD[4].

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5 Interface Requirements

5.1 Mechanical

There are no mechanical interfaces between the CSP_Low and the external VLBI equipment.

5.2 Fluid

There are no fluid interfaces between the CSP_Low and the external VLBI equipment.

5.3 Thermal

There are no thermal interfaces between the CSP_Low and the external VLBI equipment.

5.4 Electromagnetic

There are no electromagnetic interfaces between the CSP_Low and the external VLBI equipment.

5.5 Optical

There are no optical interfaces between the CSP_Low and the external VLBI equipment.

5.6 Electrical

There are no electrical interfaces between the CSP_Low and the external VLBI equipment.

5.7 Electronic

There are no electronic interfaces between the CSP_Low and the external VLBI equipment.

5.8 Electro-optical

Electro-optical interfaces between the CSP_Low and the external VLBI equipment are defined in the SKA Mid SADT to CSP ICD (AD[4]) for I.S1L.SADT_CSP.008, and in the SKA1 External VLBI Interface Control Document (RD[3]) for I.S1M.SADT_VLBI.001 (TBD03), summarized in Section 1.6.

5.9 Data exchange specifications

Table 5-1 : Data Exchange Specification Interface Requirements

Requirement ID	Title	Description
I.S1L.CSP_VLBI.001.R.001	Data packet format	CSP_Low shall transmit VLBI data packets in accordance with the VDIF Specification AD[5].

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Requirement ID	Title	Description
I.S1L.CSP_VLBI.001.R.002	Data transport protocol	CSP_Low shall transmit VLBI data packets as UDP over Ethernet in accordance with the VDIF Transport Protocol AD[6].
I.S1L.CSP_VLBI.001.R.003	Number of VLBI beams	CSP_Low shall form up to 4 dual-polarization VLBI beams across all of up to 4 station beams distributed across up to 4 sub-arrays; each VLBI beam may be on a different delay centre on the sky, within the half-power beamwidth of a SKA1_Low station beam, with beamwidth calculated for the highest observed frequency in the VLBI beam.
I.S1L.CSP_VLBI.001.R.004	Total beam bandwidth	CSP_Low, when commanded, shall form dual-polarization VLBI beams with a total bandwidth of up to 256MHz, within the 300MHz station bandwidth.
I.S1L.CSP_VLBI.001.R.005	Number of beam-channels per beam	CSP_Low, when commanded, shall form up to 4 dual-polarization beam-channels per VLBI beam. All beam-channels must be within the frequency range of a single station beam. Combined bandwidth of all beam-channels for a VLBI beam shall be up to 256MHz.
I.S1L.CSP_VLBI.001.R.006	Beam-channel bandwidth and sampling rate	CSP_Low shall support production and output of the following real dual-polarization beam-channel bandwidths: 1. 64 MHz beam-channel 2. 32 MHz beam-channel 3. 16 MHz beam-channel 4. 8 MHz beam-channel 5. 4 MHz beam-channel 6. 2 MHz beam-channel 7. 1 MHz beam-channel ***Note 1***: Only one bandwidth selectable for all beam-channels per beam ***Note 2***: All beam-channels within a VLBI beam are configurable to output single or dual polarization. ***Note 3***: CSP_Low allows a single oversampling ratio of 16/n with n from 8 to 16 for all beam-channels per beam.
I.S1L.CSP_VLBI.001.R.007	Beam-channel centre frequency	For each beam the centre frequency of each beam channel shall be (beam-channel bandwidth)x(k+0.5) + offset. Where k is an integer and "offset" is a frequency offset common to all beam-channels in a beam. "Offset" has a resolution of better than 0.01MHz. The variables "k" and "offset" must be chosen such that all beam-channels lie in the sky frequency range of 50 to 350 MHz.
I.S1L.CSP_VLBI.001.R.008	Beam-channel word size	CSP_Low shall support the following word sizes for each beam-channel independently: 1. 8-bit 2. 4-bit 3. 2-bit All outputs are real.
I.S1L.CSP_VLBI.001.R.009	Maximum output data rate	Beam-channel word size, oversampling, bandwidth, number of channels per beam and number of beams shall not produce a total output data rate greater than 80% (TBC01) utilisation of the 100 GbE link.

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Requirement ID	Title	Description
I.S1L.CSP_VLBI.001.R.010	RFI flagging and excision	CSP_Low, when commanded, shall flag and excise fine channel data for RFI per StationBeam basis. Derived VLBI beam-channels are not individually flagged and excised. CSP_Low flagging information is passed through the subsequent pipelines and modifies Low.CBF output data products. RFI excision affects both polarizations identically.
I.S1L.CSP_VLBI.001.R.011	Beam-channel output power levels[Note1]	CSP_Low shall independently measure and log each beam-channel's output power levels and internal gain settings.
I.S1L.CSP_VLBI.001.R.012	Beam-bandwidth unit polarization correction	CSP_Low, when commanded, shall apply TM-provided polarization corrections independently to each beamformed LFAA channel, as per PST processing. Polarization corrections are not additionally applied to derived tunable beam-channels.

Note1: beam-channels output power levels are not conveyed using the interfaces described in this ICD, but using the CSP Low to TM Interfaces RD[4], and will reach the VLBI equipment as part of meta-data.

The exact data rate of VLBI output from Low.CBF is highly variable based on the selection of:

1) The number of beams and beam-channels.
2) The bandwidth of each beam-channel.
3) The word size of each beam-channel.
4) The sampling rate of each beam-channel.

The total VLBI output data rate generated by CSP_Low is controlled by TM to avoid saturating the 100 GbE link. The total VLBI output data rate generated by CSP_Low also cannot overload the external VLBI equipment capacity (TBD05). The total VLBI output data rate can be calculated as follows, assuming that all beam channels have the same bandwidth:

Nbeams x Nbeam_channels x bandwidth (MHz) x 2polarisations x 2Nyquist x oversampling_ratio x Nbits (Mbps)

For example, for 4 VLBI beams with 4 beam channels of 64 MHz bandwidth each, 4-bit digitisation, and Nyquist sampling the total output data rate is 16 Gbps.

The precise population of the CSP_Low-generated VDIF frames is TBD06, to be described in the SKA1 External VLBI ICD RD[3]. However, each VDIF stream output by CSP_Low contains row data (i.e. a time series) for one particular real single or dual-polarization beam-channel.

5.9.1 Boundaries of responsibility

The CSP_Low is responsible for:

1) The transmission of VLBI data streams in accordance with the requirements.

The party that provides the external VLBI equipment is responsible for:

2) Ingestion and processing of the VLBI data produced by CSP_Low that is delivered to the VLBI equipment through the SaDT network.

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5.10 Human-Machine Interfaces

There are no direct Human-Machine interfaces between the CSP_Low and the external VLBI equipment.

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6 Interface Implementation

6.1 Mechanical

Not applicable.

6.2 Fluidic

Not applicable.

6.3 Thermal

Not applicable.

6.4 Electromagnetic

Not applicable.

6.5 Optical

Not applicable.

6.6 Electrical

Not applicable.

6.7 Electronic

Not applicable.

6.8 Electro-optical

The first physical, electro-optical interface, is provided by SaDT (I.S1L.SADT_CSP.008) and described in SKA SADT to CSP ICD, AD[4]. The second physical, electro-optical interface, is provided by the external VLBI equipment stakeholders (I.S1M.SADT_VLBI.001 TBD) and described in the SKA1 External VLBI Interface Control Document (RD[3]).

6.9 Data exchange specifications

The CSP_Low implements the VLBI interface in accordance with the VDIF specification AD[5] and VDIF Transport Protocol AD[6].

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6.10 Human-Machine Interfaces

Not applicable.

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7 Interface Verification

Interface verification occurs at many stages in the integration of the Elements. It is carried out to demonstrate that the design and implementation conform to the ICD, and it will be described in formal procedures. A key distinction is made between verification tests that require the interfacing Element and those that do not (using a simulator or standard test equipment). The ICD shall contain a section on the verification methods to be used to:

1. *Verify the design and implementation of interfacing hardware and software without the interface being made*
2. *Verify the interface for integration and acceptance purposes (involving the interface being made)*

The execution of the first case is the responsibility of the respective interfacing parties.

The SKAO provided template and the SKA Interface Management Plan *(AD[2]) identify the Leading interfacing party as responsible for specifying verification methods and procedures, and for executing them, in the second case above (interface being made). However, in the case of this interface, VLBI equipment will be provided by the party external to SKA, and the CSP Consortium cannot take responsibility for executing verification methods and procedures.*

For each interface specification, the verification method and the level at which the verification will occur must be specified.

To be completed in subsequent release.

7.1 Verification Matrix

Table 7-1 will list the stage, method and configuration used to verify each interface requirement. This version of the ICD does not provide the complete verification matrix.

Table 7-1 : Verification Cross Reference Matrix

Interface Requirement		**Verification**		
Par. No.	**Req. ID**	**Method**	**Stage**	**Configuration (list of CIs involved)**
5.9	I.S1L.CSP_VLBI.001.R.001 Data Packet Format	Test		
5.9	I.S1L.CSP_VLBI.001.R.002 Data Transport Protocol	Test		
5.9	I.S1L.CSP_VLBI.001.R.003 Number of VLBI beams	Test		
5.9	I.S1L.CSP_VLBI.001.R.004 Total beam bandwidth	Test		
5.9	I.S1L.CSP_VLBI.001.R.005 Number of beam-channels per beam	Test		

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Interface Requirement		Verification		
Par. No.	Req. ID	Method	Stage	Configuration (list of CIs involved)
5.9	I.S1L.CSP_VLBI.001.R.006 Beam-channel bandwidth and sampling rate	Test		
5.9	I.S1L.CSP_VLBI.001.R.007 Beam-channel centre frequency	Test		
5.9	I.S1L.CSP_VLBI.001.R.008 Beam-channel word size	Test		
5.9	I.S1L.CSP_VLBI.001.R.009 Maximum output data rate	Test		
5.9	I.S1L.CSP_VLBI.001.R.010 RFI flagging and excision	Demonstration		
5.9	I.S1L.CSP_VLBI.001.R.011 Beam-channel output levels	Test		
5.9	I.S1L.CSP_VLBI.001.R.012 Beam-bandwidth unit polarization correction	Test		

7.1.1 Interface not made

7.1.1.1 Mechanical

Not applicable.

7.1.1.2 Fluidic

Not applicable.

7.1.1.3 Thermal

Not applicable.

7.1.1.4 Electromagnetic

Not applicable.

7.1.1.5 Optical

Not applicable.

7.1.1.6 Electrical

Not applicable.

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7.1.1.7 Electronic

Not applicable.

7.1.1.8 Electro-optical

Not applicable.

7.1.1.9 Data exchange specifications

TBD07

7.1.1.10 Human-Machine Interface

Not applicable.

7.1.2 Interface made

7.1.2.1 Mechanical

Not applicable.

7.1.2.2 Fluidic

Not applicable.

7.1.2.3 Thermal

Not applicable.

7.1.2.4 Electromagnetic

Not applicable.

7.1.2.5 Optical

Not applicable.

7.1.2.6 Electrical

Not applicable.

7.1.2.7 Electronic

Not applicable.

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7.1.2.8 Electro-optical

Not applicable.

7.1.2.9 Data exchange specifications

TBD07

7.1.2.10 Human-Machine Interface

Not applicable.

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8 Appendix: List of TBDs and TBCs

Table 8-1 : TBDs and TBCs

Number	Section	Text	Disposition by:
TBD01	1.1, 1.6	The SaDT Element is responsible for transport of the CSP_Low VLBI output data from the CSP to the designated place in the Science Processing Centre.	SKAO
TBD02	1.2	VLBI equipment CIN number.	SKAO
TBD03	1.6, 5.8	SaDT to VLBI Interface not defined yet.	SaDT and SKAO
TBD04	3	Test, diagnostic, and maintenance features	CSP
TBD05	5.9	The total VLBI output data rate generated by CSP_Low must also not overload the external VLBI equipment.	SKAO – input bandwidth to external VLBI equipment is TBD.
TDB06	5.9	The precise population of the CSP_Low-generated VDIF frames.	SKAO
TDB07	7.1.1.9, 7.1.2.9	Verification procedures for interface not provided.	SKAO
TBC01	5.9	80% utilisation of the 100 GbE link.	SKAO

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9 Appendix: Responsibilities Matrix

Table 9-1 : Responsibilities Matrix

Requirement ID	Title	Responsibility	
		CSP	SKAO
I.S1L.CSP_VLBI.001.R.001	Data Packet Format	yes	
I.S1L.CSP_VLBI.001.R.002	Data Transport Protocol	yes	
I.S1L.CSP_VLBI.001.R.003	Number of VLBI beams	yes	
I.S1L.CSP_VLBI.001.R.004	Total beam bandwidth	yes	
I.S1L.CSP_VLBI.001.R.005	Number of beam-channels per beam	yes	
I.S1L.CSP_VLBI.001.R.006	Beam-channel bandwidth and sampling rate	yes	
I.S1L.CSP_VLBI.001.R.007	Beam-channel centre frequency	yes	
I.S1L.CSP_VLBI.001.R.008	Beam-channel word size	yes	
I.S1L.CSP_VLBI.001.R.009	Maximum output data rate		yes
I.S1L.CSP_VLBI.001.R.010	RFI flagging and excision	yes	
I.S1L.CSP_VLBI.001.R.011	Beam-channel output power levels	yes	
I.S1L.CSP_VLBI.001.R.012	Beam-bandwidth unit polarization correction	yes	

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ANNEX 2.2 MID Central Signal Processor (CSP) to VLBI ICD

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SQUARE KILOMETRE ARRAY

SKA1_MID TELESCOPE
INTERFACE CONTROL DOCUMENT
CSP TO VLBI

Document Number 300-000000-032
Document Type .... ICD
Revision 01
CSP Document Number SKA-TEL.CSP.SE-VLBI-ICD-001
Author .... Michael Pleasance
Date 2018-06-26
Document Classification .... UNRESTRICTED
Status .... Released

Name	Deassignation	Affiliation	Signature
Authored by:			
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C. Garcia-Miro	SKA VLBI Scientist	SKAO	
W. Turner	CSP IET System Engineer	SKAO	W.Turner
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J. Santander-Vela	SW and SDP System Engineer	SKAO	
Released by:			
J. McMullin	Programme Director	SKAO	J P McMullin 2018-07-15

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DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2014-05-22	-	First draft.
B	2015-10-14	-	Updated as per SKA1 re-baselining (removed information related to SKA Survey).
C	2015-11-20	CSP-PDR-OAR-093	Added requirements related to channelization. See Section 5.9. CSP_Mid will generate multithreaded output, but the exact requirements and implementation, and the exact organization of the output data are still TBD.
		CSP-PDR-OAR-094	Section 1.3.2: CSP generates output data as specified in the VLBI Data Interchange Format (VDIF) Specification, Release 1.1.1.
01	2015-11-26	-	CSP_Mid could merge/intersperse VLBI beam packets with visibility and transient buffer packets into the 64 x 100G outputs already going from CSP_Mid to the SDP via SaDT's long-haul network. Output data rate per beam 40Gsps, 2bits per sample. Delta PDR release.
01	2017-12-19		New doc # assignment
	2018-01-05	ECP-170053	Updated ICD content to match Mid.CBF FSA VLBI functionality as per ECP-170053.
	2018-01-13		Changed author; reference external VLBI ICD; incorporate responses to SKAO comments
	2018-01-15		Incorporated responses to comments from SKAO SaDT System Engineer.
	2018-01-16		Incorporated responses to comments from SKAO SDP System Engineer.
	2018-04-27		Incorporated responses to comments from MID System Engineer. Added SDP as a carrier. Updated the interface topology including SDP. Included missing aspects of the data exchange specifications.
	2018-05-10		Added referenced to SDP to CSP ICD for the information on how the VDIF packets will be interspersed with visibilities and added this ICD to the list of applicable documents. Updated Figure 1-1 to show the involvement of SDP in the transport of VLBI data from CSP to the external VLBI equipment. Added a row to the TBC/TBD table to note that Nyquist sampling rates have been assumed and an ECP is pending.

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			Added total VLBI output data rate calculation. Changed Interface Requirement ID.
	2018-06-12		Incorporated responses to comments from SaDT and SDP Consortia. Updated Interface Topology and related text adding SDP-CSP interface. Aligned Interface requirements described in this ICD with L2 CSP requirements.
	2018-06-15		Fixed formatting issues. Fixed inconsistent use of terminology and proper noun use. Fixed grammar issues. Fixed Heading 2 indent problem. Removed "will be" future tense. Fixed text links to "RD[3]". Incorporated responses to comments from SKAO System Engineers (SaDT and CSP IET).
01	2018-06-26		First Revision Released

DOCUMENT SOFTWARE

	Package	Version	Filename
Word processor			300-000000-032-01_CSPMid-to-VLBI_ICD
Block diagrams			
Other			

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington, Macclesfield Cheshire SK11 9DL Registered in England & Wales Company Number: 07881918
Website	www.skatelescope.org

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TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF FIGURES

LIST OF TABLES

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LIST OF ABBREVIATIONS

CIN ....Configuration Item (number)
CSP ....Central Signal Processor Element
CSP_Mid ....Central Signal Processor in the SKA1_Mid Telescope
HMI................................Human-Machine Interface
ICD ....Interface Control Document
OSI ....Open Systems Interconnection
SADT.............................Signal and Data Transport Element
SDP ....Science Data Processor Element
SKA ....Square Kilometre Array
SKAO ....SKA Organization
TBC ....To Be Confirmed
TBD ....To Be Decided
TM ....Telescope Manager
UDP...............................User Datagram Protocol
VDIF ....VLBI Data Interchange Format
VLBI...............................Very Long Baseline Interferometry
VTP ....VDIF Transport Protocol

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1 Introduction

1.1 Scope and purpose

This document defines the interfaces between the SKA1_Mid Central Signal Processor (CSP_Mid) Element and the externally-supplied VLBI equipment. The capabilities described are those provided by CSP_Mid; this does not guarantee that these full capabilities are supported by TM and the telescope as a whole at the end of construction. This document should be read in conjunction with the SKA1 External VLBI ICD RD[3], which contain details about the VLBI terminal, the VDIF data format, required metadata, and their format, etc.

The basic breakdown of VLBI data transport responsibilities is as follows:

1) CSP_Mid provides 80 x 100GE fibre outputs for visibility and VLBI data which connect to SDP Ethernet switches.
2) The SaDT Element is responsible for transport of CSP_Mid VLBI output data from CSP_Mid to the SDP Ethernet switches.
3) The SDP Ethernet switches are protected by an Edge Security device (i.e. firewall) from where the VLBI equipment is connected. External VLBI equipment stakeholders are responsible for data links from the SDP Edge Security device to the location of the external VLBI equipment in the designated place (TBD01) in the Science Processing Centre.

This document complies with the SKA Interface Management Plan AD[2].

1.2 Interface Identification

This Interface Control Document (ICD) defines the requirements and implementation details of the interface:

I.S1M.CSP_VLBI.001 "SKA1 Mid Central Signal Processor to VLBI Interface".

[Note: the interface identifier used is I.S1t.xxx_yyy.nnn, where:
S = SKA,
1 = Phase 1,
t = Telescope: M for Mid.
Xxx = Interfacing Element 1
Yyy = Interfacing Element 2
nnn = identification number]

This interface involves the following items of the SKA1 Mid Telescope:

1) CSP_Mid Correlator and Beamformer (CBF) (Configuration Item Number (CIN) 311-000000)
2) External VLBI equipment (Configuration Item Number (CIN) TDB02)

CIN number for VLBI equipment (TBD02) is specified in the SKA1 External VLBI Interface Control Document RD[3].

1.2.1 Interface Requirement Identification

Within the ICD, when only one interface is described, requirements are identified as follows:

R.nnn *[nnn is an identification number].*

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If more than one interface is represented in one ICD, then a Unique Interface Requirement Identification Label (UIRIL) is used and defined as follows:

IIC.R.nnn *[IIC=Interface Identification Code, R stands for Requirement, nnn is an identification number]*

1.3 Applicable and Reference documents

1.3.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of a conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

AD[1] SKA Project Safety Management Plan ", SKA-TEL-SKO-0000740, Rev 01

AD[2] SKA1 Interface Management Plan, SKA-TEL-SKO-0000025, ver 02

AD[3] SKA Phase 1 System (Level 1) Requirements Specification, SKA-TEL-SKO-0000008, Rev 11

AD[4] INTERFACE CONTROL DOCUMENT SADT TO CSP (MID), 300-000000-023, Rev 3

AD[5] INTERFACE CONTROL DOCUMENT SDP TO CSP (MID), 300-000000-002, Rev 3

AD[6] INTERFACE CONTROL DOCUMENT SADT TO SDP (MID), 300-000000-025, Rev 4

AD[7] VLBI Data Interchange Format (VDIF) Specification, Release 1.1.1, June 2014, http://vlbi.org/vdif/docs/VDIF_specification_Release_1.1.1.pdf

AD[8] VTP: VDIF Transport Protocol, Release 1.0.0, 30 October 2013, http://vlbi.org/docs/2013.10.30_VTP_rev_1.0.pdf

1.3.2 Reference documents

The following documents are referenced in this document. In the event of a conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

RD[1] SKA1 CSP Element Requirements Specification (SE-2), SKA-TEL-CSP-0000010, Rev 5

RD[2] SKA1 CSP Mid Correlator and Beamformer Sub-element Detailed Design Document (EB-4a), 311-000000-003

RD[3] SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116, to be released

RD[4] INTERFACE CONTROL DOCUMENT CSP Mid TO TM, 300-000000-021, Rev 03

1.4 Roles and responsibilities

Table 1-1 defines the roles and responsibilities of the relevant parties.

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Table 1-1 : Roles and responsibilities

Role	Organization	Point of contact	Responsibilities
Author	CSP Consortium	CSP_Mid.CBF Lead Engineer	Create and maintain this document
Leading party	CSP Consortium	CSP_Mid System Engineer	Contribute to, review and approve this document
Approving party	SKAO	CSP IET System Engineer	Contribute to, review and approve this document
Owning party	SKAO	MID System Engineer	Oversight, approval and release
Reviewer	SaDT Consortium	SaDT Consortium Lead	Review and approve this document
Reviewer	SKAO	SaDT System Engineer	Review and approve this document
Reviewer	SDP Consortium	SDP System Engineer	Review and approve this document
Reviewer	SKAO	SW and SDP System Engineer	Review and approve this document

1.5 Interface scope

Table 1-2 lists the classes of interface specification included in this document.

Table 1-2 : Interface class specifications

Interface class	Included in document?
Mechanical	N
Fluid	N
Thermal	N
Electromagnetic	N
Optical	N
Electrical	N
Electronic	N
Electro-optical	N
Data exchange specifications	**Y**
Human-Machine Interface	N

1.6 Interface topology

The interfaces described in this document are between the CSP Element and the external VLBI equipment. The SADT Element provides the OSI physical layer (Layer 1) connection between CSP_Mid and the SDP. This physical layer consists of the same 80 x 100GbE fibre optic links that are used for transport of visibility and transient buffer data from CSP_Mid.CBF to SDP via interfaces

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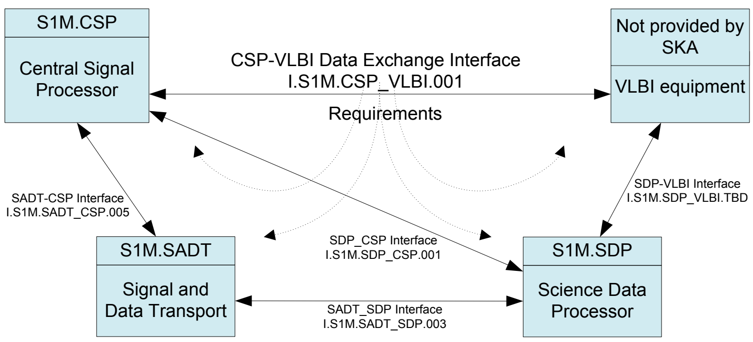
I.S1M.SDP_CSP.001, I.S1M.SADT_CSP.005 and I.S1M.SADT_SDP.003, as described in the SKA1 Mid SADT to CSP ICD (AD[4]), Mid SDP to CSP (AD[5]), and Mid SADT to SDP ICD (AD[6]). VLBI VDIF packets are interspersed / merged with visibility and transient buffer SPEAD packets on the same 80 x 100GbE fibre optic links. The various data flows sharing the 80 x 100GbE fibre optic links are described in the Mid SDP to CSP ICD (AD[5]). The allocation of bandwidth to each of the data product types is managed by TM.

The following assumptions are made:

1) The SaDT Element is responsible for transport of CSP_Mid VLBI output data from CSP_Mid to the SDP Ethernet switches.
2) The external VLBI equipment stakeholders are responsible for data links from the SDP Edge Security device to the location of the external VLBI equipment in the designated place (TBD01) in the Science Processing Centre. This interface has been defined as I.S1M.SDP_VLBI.TBD (TBD03) to be documented in RD[3].

Figure 1-1 Interface Topology



1.7 Summary of standards rationales

CSP_Mid transmits VLBI data using the VDIF format, which is in extensive use by the VLBI community AD[7]. Thus, to provide compatibility of the SKA1 Mid VLBI 'station' with existing and planned VLBI equipment, CSP_Mid adopts this standard for VLBI beam data output.

1.8 Data packet format

The output of the CSP_Mid Element is compatible with the VLBI Data Interface Specification (VDIF) AD[7].

1.9 Data transport protocol

Data packets are streamed as UDP over Ethernet in accordance with the VDIF Transport Protocol AD[8].

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2 Specification Class List and Applicable Standards

2.1 Data Exchange Specifications

CSP_Mid implements the following standards:

1) VLBI Data Interchange Format (VDIF) Specification, AD[7].
2) VTP: VDIF Transport Protocol, AD[8].

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3 Test, Diagnostic or Maintenance Features

Any design features provided at the interface exclusively for testing, diagnosis or maintenance procedures, for the interface itself, shall be documented in this section. The presentation of these features shall follow the same logic as that for the main interface.

To be completed in subsequent release (TBD04).

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4 Safety Aspects

Safety aspects of interfaces arise from application of the safety provisions of the SKA Project Safety Management Plan AD[1], such as the mandatory Safety Assessment. In addition to the products of the Safety programme, safety critical interfaces shall be highlighted in ICDs as in any other design or operations related documents.

Safety concerns have not been identified so far. Note that safety concerns related to lasers are addressed by the ICD SADT to CSP, AD[4].

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5 Interface Requirements

5.1 Mechanical

There are no mechanical interfaces between CSP_Mid and the external VLBI equipment.

5.2 Fluid

There are no fluid interfaces between CSP_Mid and the external VLBI equipment.

5.3 Thermal

There are no thermal interfaces between CSP_Mid and the external VLBI equipment.

5.4 Electromagnetic

There are no electromagnetic interfaces between CSP_Mid and the external VLBI equipment.

5.5 Optical

There are no optical interfaces between CSP_Mid and the external VLBI equipment.

5.6 Electrical

There are no electrical interfaces between CSP_Mid and the external VLBI equipment.

5.7 Electronic

There are no electronic interfaces between CSP_Mid and the external VLBI equipment.

5.8 Electro-optical

Electro-optical interfaces between CSP_Mid and the external VLBI equipment are defined in the SKA1 Mid SADT to CSP ICD (AD[4]) for I.S1M.SADT_CSP.005, in the Mid SADT to SDP ICD (AD[6]) for I.S1M.SADT_SDP.003, and in the SKA1 External VLBI Interface Control Document (RD[3]) for I.S1M.SDP_VLBI.TBD (TBD03), summarized in Section 1.6.

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5.9 Data exchange specifications

Table 5-1 : Data Exchange Specification Interface Requirements

Requirement ID	Title	Description
I.S1M.CSP_VLBI.001.R.001	Data packet format	CSP_Mid shall transmit VLBI data packets in accordance with the VDIF Specification AD[7].
I.S1M.CSP_VLBI.001.R.002	Data transport protocol	CSP_Mid shall transmit VLBI data packets as payloads in UDP over Ethernet in accordance with the VDIF Transport Protocol AD[8].
I.S1M.CSP_VLBI.001.R.003	Number of VLBI beams	CSP_Mid shall form at least 208 dual-polarization VLBI beams across at least 4 VLBI sub-arrays and, if possible, up to 520 dual-polarization VLBI beams across all of up to 16 sub-arrays, with a maximum of 52 beams per sub-array; each beam may be on a different delay centre on the sky, within the half-power beamwidth of the SKA1_Mid antenna, calculated for the highest observed frequency in the beam. The number of VLBI beams that may be formed depends on the number of CSP_Mid Frequency Slice Processors (FSPs) assigned to VLBI processing. There are a total of 26 FSPs and each FSP can form up to 20 VLBI beams in up to 16 sub-arrays, with a maximum of 2 VLBI beams per sub-array per FSP.
I.S1M.CSP_VLBI.001.R.004	Beam-bandwidth unit	CSP_Mid, when commanded, shall form dual-polarization beams in "beam-bandwidth units" of 224 MHz per polarization, with the central 200 MHz usable for science. The beam-bandwidth unit is selected from one of the contiguous and overlapping Frequency Slices, produced from the digitized Band, for the sub-array. Wider total beam bandwidths (up to the total SKA1 bandwidth for a given Band) can be achieved with multiple 224 MHz beam-bandwidth units, co-located on the sky, and formed from adjacent Frequency Slices. 224 MHz beam-bandwidth units that are adjacent in frequency are overlapped and therefore provide contiguous science bandwidth coverage (i.e. the central 200 MHz bandwidths from adjacent Frequency Slices are contiguous in frequency).

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Requirement ID	Title	Description
I.S1M.CSP_VLBI.001.R.005	Number of beam-channels per beam	CSP_Mid, when commanded, shall form up to at least 624 dual-polarization beam-channels. Up to 520 of the dual-polarization beam-channels may contain the full 224 MHz of the beam-bandwidth unit (and in this case the beam-channels are, in fact, beam-bandwidth units). Up to 416 beam-channels are tunable and derived from source 224 MHz beam-bandwidth units. Each of these has a configurable centre frequency and bandwidth within the source 224 MHz beam-bandwidth unit. Each FSP performing VLBI processing can produce and output up to 20 x 224 MHz dual-polarization beam-channels and up to 24 tunable dual-polarization beam-channels. Tunable beam-channels can be assigned (in groups of 4) to any of the 20 VLBI beam-bandwidth units formed by the FSP.
I.S1M.CSP_VLBI.001.R.006	Tunable beam-channels centre frequency	Each tunable beam-channel shall be independently tuned anywhere within the source 224 MHz beam-bandwidth unit with a 0.01 MHz tuning resolution.
I.S1M.CSP_VLBI.001.R.007	Beam-channel bandwidth and sampling rate	CSP_Mid shall support production and output of the following real dual-polarization beam-channel bandwidths and Nyquist sample rates (TBD07): 1. 224 MHz (448 Ms/s) full beam bandwidth 2. 128 MHz (256 Ms/s) tunable beam-channel 3. 64 MHz (128 Ms/s) tunable beam-channel 4. 32 MHz (64 Ms/s) tunable beam-channel 5. 16 MHz (32 Ms/s) tunable beam-channel 6. 8 MHz (16 Ms/s) tunable beam-channel 7. 4 MHz (8 Ms/s) tunable beam-channel 8. 2 MHz (4 Ms/s) tunable beam-channel 9. 1 MHz (2 Ms/s) tunable beam-channel ***Note 1***: For bandwidths 1, 2, …, 128 MHz, the central 82% of the bandwidth is usable for science. ***Note 2***: Each beam-channel is independently configurable to output single or dual polarization. There is no ability to trade off single/dual polarization to increase the number of beams, beam-bandwidth units, or tunable beam-channels. However, selecting single polarization allows for greater aggregate bandwidth output capability over the limited CSP_Mid-to-VLBI equipment link capacity.
I.S1M.CSP_VLBI.001.R.008	Beam-channel word size	CSP_Mid shall support the following word sizes for each beam-channel independently: 1. 16-bit 2. 8-bit 3. 4-bit 4. 2-bit All outputs are real.

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Requirement ID	Title	Description
I.S1M.CSP_VLBI.001.R.009	Maximum output data rate	Beam-channel word size, bandwidth, number of channels per beam and number of beams shall not produce a total output data rate greater than the available CSP_Mid-to-VLBI equipment link capacity (TBD05).
I.S1M.CSP_VLBI.001.R.010	RFI flagging and excision	CSP_Mid, when commanded, shall flag and excise each 224 MHz beam-bandwidth unit for RFI. Derived tunable beam-channels are not individually flagged. Flagging information is not explicitly conveyed with the data across this interface, instead CSP_Mid automatically adjusts for per-receptor, per-beam-bandwidth unit flagging to maintain constant output beam-channel signal level. CSP_Mid logs per-beam-bandwidth unit RFI flagging statistics. In the case where all receptors are flagged and excised, the signal level is maintained to within +/-20% with an internal broad-band signal generator. RFI excision affects both polarizations identically.
I.S1M.CSP_VLBI.001.R.011	Beam-channel output power levels[Note1]	CSP_Mid, when commanded, shall automatically and individually adjust beam-channel output signal levels (each polarization individually) for optimum sensitivity and RFI headroom — where fundamentally possible maintaining at least 4 bits on the sky signal of interest. CSP_Mid shall independently measure and log each beam-channel's output power levels and internal gain settings.
I.S1M.CSP_VLBI.001.R.012	Beam-bandwidth unit polarization correction	CSP_Mid, when commanded, shall apply TM-provided polarization corrections independently to each beamformed 224 MHz beam-bandwidth unit. Polarization corrections are not additionally applied to derived tunable beam-channels.

Note1: beam-channels output power levels are not conveyed using the interfaces described in this ICD, but using the CSP Mid to TM Interfaces RD[4], and will reach the VLBI equipment as part of meta-data.

The exact data rate of VLBI output from Mid.CBF is highly variable based on the selection of:

1) The number of beams and beam-channels.
2) The bandwidth of each beam-channel.
3) The word size of each beam-channel.

The total VLBI output data rate generated by CSP_Mid is controlled by TM to avoid saturating the 80 x 100 GbE links, which are also used for visibility and transient buffer data flows. The total VLBI output data rate generated by CSP_Mid also cannot overload external VLBI equipment capacity (TBD05). The total VLBI output data rate can be calculated as follows, assuming that all beam channels have the same bandwidth:

Nbeams x Nbeam_channels x bandwidth (MHz) x 2polarisations x 2Nyquist sampling x Nbits (Mbps)

If beam channels have different bandwidths the term (*Nbeam_channels x bandwidth*) should be substituted by the total bandwidth (summation) from all of the different beam channels.

For example, for 4 VLBI beams each with 4 beam channels of 128 MHz bandwidth each, 4-bit digitisation, and Nyquist sampling, the total output data rate is 32 Gbps.

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The precise population of the CSP_Mid-generated VDIF frames is TBD06, to be described in the SKA1 External VLBI ICD RD[3]. However, each VDIF stream output by CSP_Mid contains row data (i.e. a time series) for one particular real single or dual-polarization beam-channel.

5.9.1 Boundaries of responsibility

CSP_Mid is responsible for:

1) Transmission of VLBI data streams in accordance with the requirements.

The party that provides the external VLBI equipment is responsible for:

2) Ingestion and processing of VLBI data produced by CSP_Mid, which is delivered to the external VLBI equipment through the SaDT network and the SDP switches via an Edge security device.

5.10 Human-Machine Interfaces

There are no direct Human-Machine interfaces between CSP_Mid and the external VLBI equipment.

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6 Interface Implementation

6.1 Mechanical

Not applicable.

6.2 Fluidic

Not applicable.

6.3 Thermal

Not applicable.

6.4 Electromagnetic

Not applicable.

6.5 Optical

Not applicable.

6.6 Electrical

Not applicable.

6.7 Electronic

Not applicable.

6.8 Electro-optical

The first physical electro-optical interface, is provided by SaDT (I.S1M.SADT_CSP.005) and described in SKA SADT to CSP ICD, AD[4]. The second physical electro-optical interface, is provided by SaDT (I.S1M.SADT_SDP.003) and described in SKA SADT to SDP ICD, AD[4]. The third physical electro-optical interface, is provided by the external VLBI equipment stakeholders (I.S1M.SDP_VLBI.TBD) and described in the SKA1 External VLBI Interface Control Document (RD[3]).

6.9 Data exchange specifications

CSP_Mid implements the VLBI interface in accordance with the VDIF specification AD[7] and the VDIF Transport Protocol AD[8].

6.10 Human-Machine Interfaces

Not applicable.

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7 Interface Verification

Interface verification occurs at many stages in the integration of the Elements. It is carried out to demonstrate that the design and implementation conform to the ICD, and it will be described in formal procedures. A key distinction is made between verification tests that require the interfacing Element and those that do not (using a simulator or standard test equipment). The ICD shall contain a section on the verification methods to be used to:

1. *Verify the design and implementation of interfacing hardware and software without the interface being made*
2. *Verify the interface for integration and acceptance purposes (involving the interface being made)*

The execution of the first case is the responsibility of the respective interfacing parties.

The SKAO provided template and the SKA Interface Management Plan *(AD[2]) identify the Leading interfacing party as responsible for specifying verification methods and procedures, and for executing them, in the second case above (interface being made). However, in the case of this interface, VLBI equipment will be provided by the party external to SKA, and the CSP Consortium cannot take responsibility for executing verification methods and procedures.*

For each interface specification, the verification method and the level at which the verification will occur must be specified.

To be completed in subsequent release.

7.1 Verification Matrix

Table 7-1 lists the stage, method, and configuration used to verify each interface requirement. This version of the ICD does not provide the complete verification matrix.

Table 7-1 : Verification Cross Reference Matrix

Interface Requirement		**Verification**		
Par. No.	**Req. ID**	**Method**	**Stage**	**Configuration (list of CIs involved)**
5.9	I.S1M.CSP_VLBI.001.R.001 Data Packet Format	Test		
5.9	I.S1M.CSP_VLBI.001.R.002 Data Transport Protocol	Test		
5.9	I.S1M.CSP_VLBI.001.R.003 Number of VLBI Beams	Test		
5.9	I.S1M.CSP_VLBI.001.R.004 Beam-bandwidth unit	Test		
5.9	I.S1M.CSP_VLBI.001.R.005 Number of beam-channels per beam	Test		

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Interface Requirement		Verification		
Par. No.	Req. ID	Method	Stage	Configuration (list of CIs involved)
5.9	I.S1M.CSP_VLBI.001.R.006 Tunable beam-channels centre frequency	Test		
5.9	I.S1M.CSP_VLBI.001.R.007 Beam-channel bandwidth and sampling rate	Test		
5.9	I.S1M.CSP_VLBI.001.R.008 Beam-channel word size	Test		
5.9	I.S1M.CSP_VLBI.001.R.009 Maximum output data rate	Test		
5.9	I.S1M.CSP_VLBI.001.R.010 RFI flagging and excision	Demonstration		
5.9	I.S1M.CSP_VLBI.001.R.011 Beam-channel output power levels	Test		
5.9	I.S1M.CSP_VLBI.001.R.012 Beam-bandwidth unit polarization correction	Test		

7.1.1 Interface not made

7.1.1.1 Mechanical

Not applicable.

7.1.1.2 Fluidic

Not applicable.

7.1.1.3 Thermal

Not applicable.

7.1.1.4 Electromagnetic

Not applicable.

7.1.1.5 Optical

Not applicable.

7.1.1.6 Electrical

Not applicable.

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7.1.1.7 Electronic

Not applicable.

7.1.1.8 Electro-optical

Not applicable.

7.1.1.9 Data exchange specifications

TBD08

7.1.1.10 Human-Machine Interface

Not applicable.

7.1.2 Interface made

7.1.2.1 Mechanical

Not applicable.

7.1.2.2 Fluidic

Not applicable.

7.1.2.3 Thermal

Not applicable.

7.1.2.4 Electromagnetic

Not applicable.

7.1.2.5 Optical

Not applicable.

7.1.2.6 Electrical

Not applicable.

7.1.2.7 Electronic

Not applicable.

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7.1.2.8 Electro-optical

Not applicable.

7.1.2.9 Data exchange specifications

TBD08

7.1.2.10 Human-Machine Interface

Not applicable.

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8 Appendix: List of TBDs and TBCs

Table 8-1 : TBDs and TBCs

Number	Section	Text	Disposition by:
TBD01	1.1,1.6	The SaDT Element is responsible for transport of CSP_Mid VLBI output data from CSP_Mid to the designated place in the Science Processing Centre.	SKAO
TBD02	1.2	VLBI equipment CIN number.	SKAO
TBD03	1.6, 5.8	SDP to VLBI Interface not defined yet.	SDP and SKAO
TBD04	3	Test, diagnostic, and maintenance features	CSP
TBD05	5.9	The total VLBI output data rate generated by CSP_Mid must also not overload the external VLBI equipment.	SKAO – input bandwidth to external VLBI equipment is TBD.
TBD06	5.9	The precise population of the CSP_Mid-generated VDIF frames.	SKAO
TBD07	5.9	Nyquist sampling rates have been assumed, pending an ECP to modify the appropriate L1 requirements.	SKAO
TBD08	7.1.1.9, 7.1.2.9	Verification procedures for interface not provided.	SKAO

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9 Appendix: Responsibilities Matrix

Table 9-1 : Responsibilities Matrix

Requirement ID	Title	Responsibility	
		CSP	SKAO
I.S1M.CSP_VLBI.001.R.001	Data Packet Format	yes	
I.S1M.CSP_VLBI.001.R.002	Data Transport Protocol	yes	
I.S1M.CSP_VLBI.001.R.003	Number of VLBI beams	yes	
I.S1M.CSP_VLBI.001.R.004	Beam-bandwidth unit	yes	
I.S1M.CSP_VLBI.001.R.005	Number of beam-channels per beam	yes	
I.S1M.CSP_VLBI.001.R.006	Tunable beam-channels centre frequency	yes	
I.S1M.CSP_VLBI.001.R.007	Beam-channel bandwidth and sampling rate	yes	
I.S1M.CSP_VLBI.001.R.008	Beam-channel word size	yes	
I.S1M.CSP_VLBI.001.R.009	Maximum output data rate		yes
I.S1M.CSP_VLBI.001.R.010	RFI flagging and excision	yes	
I.S1M.CSP_VLBI.001.R.011	Beam-channel output power levels	yes	
I.S1M.CSP_VLBI.001.R.012	Beam-bandwidth unit polarization correction	yes	

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ANNEX 2.3 Telescope Manager (TM) to VLBI ICD

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SKA1 INTERFACE CONTROL DOCUMENT
SKA1 TELESCOPE MANAGER TO VLBI TERMINAL

Document Number SKA-TEL-SKO-0000932
Document Type .... ICD
Revision....................01
Author....................P.S. Swart
Date.................... 2018-08-17
Document Classification .... FOR PROJECT USE ONLY
Status .... Released

Name	Designation	Affiliation	Signature	
Authored by:				
Paul Swart	TM System Engineer	TM Consortium	PS Swart Date:	Sep 25, 2018
Owned by:				
Andrea Cremonini	MID System Engineer	SKAO	Date:	Nov 8, 2018
Approved by:				
Paul Swart	TM System Engineer	TM Consortium	PS Swart Date:	Sep 25, 2018
Keith Grainge	SaDT Consortium Lead	SaDT Consortium	Keith Grainge Date:	Nov 20, 2018
Ferdl Graser	SDP System Engineer	SDP Consortium	Ferdl Graser Date:	Nov 19, 2018

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Cristina Garcia-Miro	SKA VLBI Scientist	SKAO		Date: Nov 8, 2018
Marco Caiazzo	Senior System Engineer	SKAO		Date: Nov 19, 2018
Rodrigo Olguin	SaDT Element System Engineer	SKAO	Rodrigo Olguin M.	Date: Nov 20, 2018
Daniel Hayden	LOW System Engineer	SKAO	D. Hayden	Date: Nov 19, 2018
Andrea Cremonini	MID System Engineer	SKAO		Date: Nov 8, 2018
Released by:				
J. McMullin	Programme Director	SKAO	J P McMullin	Date: Nov 21, 2018

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DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2018-04-13	-	TMCDR-110: Need to do a TM-VLBI ICD. TMCDR-502: VLBI External Interface identification. TMCDR-663: VLBI Projects.
B	2018-05-16	-	Updated with inputs of VLBI Scientist.
C	2018-06-20	-	Further updates.
01	2018-08-17	-	Updated after review for sign-off.

DOCUMENT SOFTWARE

	Package	Version	Filename
Word processor	MS Word	Word 2010	SKA-TEL-SKO-0000932-01_SKA1ICD-SKA1TMtoVLBITerminal.docx
Block diagrams	Ms PowerPoint	PowerPoint 2010	TM - VLBI data exchange.pptx

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington Macclesfield Cheshire SK11 9DL United Kingdom Registered in England & Wales Company Number: 07881918
Fax.	+44 (0)161 306 9600
Website	www.skatelescope.org

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TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF FIGURES

LIST OF TABLES

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LIST OF ABBREVIATIONS

AIV................................Assembly Integration and Verification
arg ....argument
attr ....attribute
CBF ....Correlator Beam Former
CI..................................Configuration Item
CPF ....Central Processing Facility
CORBA.........................Common Object Request Broker Architecture
enum ....enumerated
FQDN ....Fully Qualified Domain Name
GPS..............................Global Positioning System
ICD ....Interface Control Document
IIOP ....Internet Inter-ORB Protocol
JSON............................JavaScript Object Notation
LMC..............................Local Monitoring and Control
NTP ....Network Time Protocol
OLE ....Object Linking and Embedding
ORB..............................Object Request Broker
OSI ....Open Systems Interconnection
pps................................pulse per second
RFI................................Radio Frequency Interference
SaDT ....Signal and Data Transport
SDP ....Science Data Processor
SEFD............................System Equivalent Flux Density
SKA ....Square Kilometre Array
SKAO ....SKA Project Office
TACO ....Telescope and Accelerator Controlled with Objects
TANGO.........................TACO Next Generation Objects
TBC ....To Be Confirmed
TBD ....To Be Determined
TCP ....Transfer Control Protocol
TM ....Telescope Manager
UA ....Unified Architecture
vs..................................versus
VEX ....VLBI Experiment (definition)
VLBI..............................Very Long Baseline Interferometry
XML ....EXtensible Markup Language

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LIST OF DEFINITIONS

VLBI Terminal	A combination of hardware and software which provides a robust and standardised interface to allow a telescope to act as a component in a VLBI array. The interface provides a fully defined port which makes telescope resources available in accordance with VLBI use cases and allows the transmission of data streams in accordance with the VLBI Data Interchange Format (https://vlbi.org/vdif/).

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1 Introduction

1.1 Background

The various external interfaces between the Square Kilometre Array Phase 1 (SKA1) elements are defined in the Interface management plan [AD1].

The SKA1 Observatory comprises of the SKA1 MID Telescope, the SKA1 LOW Telescope and the SKA1 Common. Each of the SKA1 telescopes will be able to provide beam data for use by Very Long Baseline Interferometry (VLBI) equipment. VLBI Terminal will not be part of the SKA1 Observatory.

Each of the SKA1 MID and SKA1 LOW Telescopes will be attended by a Telescope Manager (TM) sub-system. The TM for the SKA1 MID Telescope is referred to by TM MID, and that of the SKA1 LOW Telescope is referred to as TM LOW. For information on the context and required functionality of TM MID and TM LOW, refer to [RD13] and [RD14] respectively. When referring to common aspects of TM MID and TM LOW, the term TM is used.

1.2 Scope of the Document

This document defines the agreed-to interfaces between the following SKA1 items in the South African SKA site:

- SKA1-Mid Telescope Manager (TM MID) (303-000000 Configuration Item Number),
- VLBI Terminal.

This document defines the agreed-to interfaces between the following SKA1 items in the Australian SKA site:

- SKA1-Low Telescope Manager (TM LOW) (103-000000 Configuration Item Number),
- VLBI Terminal.

This version of this document does not consider a specific VLBI Terminal, but rather the anticipated type of VLBI Terminal, describing a generic interface between TM and VLBI Terminal. The reason for this is to ensure standardisation on the interface between TM and future VLBI Terminal. In future versions of this document the interfaces to specific VLBI Terminal instances will be described in more detail.

Refer to the SKA1 to VLBI Interface Control Document [RD16] for a high level view of interfaces between SKA1 and VLBI. That document will also describe the API provided by TM Observatory to ingest VEX files as part of a successful VLBI proposal.

1.3 Interface Identification

Note: The interface identifier used is S1t.TM.XXX.nnn, where:

- S1 = SKA1,
- t = Telescope: M for MID, L for LOW,
- XXX = interfacing element 1 (leading party),
- YYY = interfacing element 2 (following party),
- nnn = identification number.

This Interface Control Document (ICD) defines the requirements and implementation details of the following data exchange interfaces:

a) I.S1M.TM_VLBI.001 TM MID to VLBI Terminal Interface,

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b) I.S1L.TM_VLBI.001 TM LOW to VLBI Terminal Interface.

This interface involves the following items of the SKA1-Mid and SKA1-Low Telescopes:

- TM Mid (Configuration Item (CI) number 303-000000)
- TM Low (Configuration Item (CI) number 103-000000)

CI number for VLBI equipment (TBD) will be specified at the SKA1 External VLBI Interface Control Document [RD16].

1.4 Roles and Responsibilities

Table 1 shows the roles and responsibilities for the relevant parties.

Table 1: Roles and Responsibilities

Role	Organisation	Point of Contact	Responsibilities
Author	TM Consortium	TM System Engineer	Create and maintain this document.
Leading Party	TM Consortium	TM System Engineer	Responsible for defining the implementation details; for providing methods and procedures for verification of the interface; for verifying the interface for integration and acceptance purposes; and for verification of TM MID hardware and software (without the interface being made).
Following Party	SKA Project Office (SKAO)	VLBI Scientist & SKAO SW System Engineer	Responsible for contributing to, reviewing and approval of the ICD; and ensuring that verification of VLBI interfacing hardware and software (without the interface being made) is done.
Owning Party	SKAO	MID System Engineer LOW System Engineer	Oversight, approval and release.
Reviewer	Signal and Data Timing (SaDT) Consortium	SaDT System Engineer or SaDT Consortium Leader	Review and approve this document.
Reviewer	SDP Consortium	SDP System Engineer	Review and approve this document.
Reviewer	SKAO	SKAO SaDT System Engineer	Review and approve this document.
Reviewer	SKAO	SKAO SDP System Engineer	Review and approve this document.

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2 References

2.1 Applicable Documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

[AD1] SKA-TEL-SKO-0000025, "SKA Interface Management Plan", Rev 02.
[AD2] SKA-TEL-SKO-0000008, "SKA Phase 1 System Requirements Specification", Rev 11.
[AD3] SKA-TEL-SKO-0000740, "SKA Project Safety Management Plan", Rev 01.
[AD4] RFC 793, "Transmission Control Protocol, Protocol Specification", IETF, Sep. 1981.
[AD5] S. Deering and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", RFC 2460, 1998.

2.2 Reference Documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD1] SKA-TEL-SKO-0000153, "SKA1 Interface Control Document TM to SaDT", Rev 02.
[RD2] 100-000000-001, "SKA LOW Telescope Functional Architecture", Rev 02.
[RD3] 300-000000-001, "SKA_MID Functional Architecture", Rev 03.
[RD4] ISO/IEC 7498-1:1994, "Information Technology – Open Systems Interconnection – Basic Reference Model".
[RD5] SKA-TEL-TM-0000052, "SKA1 TM System Engineering Management Plan", Rev 03.
[RD6] The TANGO Team, "The TANGO Control System Manual", Version 9.2.5.
[RD7] Common Object Request Broker Architecture (CORBA) Specification: Part 1 - Interfaces, Version 3.3.
[RD8] P Hintjens, "ØMQ Reference Guide", viewed 2016-08-17, http://zguide.zeromq.org/page:all
[RD9] 000-000000-012, "SKA1 TANGO Naming Convention (CS_Guidelines Volume 2)", Rev 01.
[RD10] 000-000000-011, "SKA TANGO Developers Guidelines (CS_Guidelines Volume 1)", Rev 01.
[RD11] SKA-TEL-AIV-2310004, "Interface Control Document MeerKAT to SKA1_MID TM", Rev 02.
[RD12] 000-000000-010, "SKA1 Control System Guidelines (CS_GUIDELINES Main Volume)", Rev 01.
[RD13] 303-000000-001, "SKA1 TM MID Requirements Specification", Rev 03.
[RD14] 103-000000-001. "SKA1 TM LOW Requirements Specification", Rev 03.
[RD15] 300-000000-025, "SKA1 MID SADT to SDP Interface Control Document", Rev 04.
[RD16] SKA-TEL-SKO-0000116, "Interface Control Document SKA1 to VLBI External Interface", Rev 01, Planned.
[RD17] Unknown, "VEX Definition", https://safe.nrao.edu/wiki/bin/view/VLBA/Vex2doc, viewed 2018-05-15.
[RD18] 103-000000-003, "SKA1 TM LOW Test Specification", Rev 02.
[RD19] 303-000000-003, "SKA1 TM MID Test Specification", Rev 02.
[RD20] T0000-0000-005, "SKA1 TM Verification Plan", Rev 02.
[RD21] SKA-TEL-AIV-4430001, "Integration and Verification Plan for SKA1_LOW", Rev 1.
[RD22] SKA-TEL-AIV-2430001, "Integration and Verification Plan for SKA1_MID", Rev 1.

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3 Test, Diagnostic or Maintenance Features

[Any design features provided at the interface exclusively for testing, diagnosis or maintenance procedures, for the interface itself, shall be documented in this section. The presentation of these features shall follow the same logic as that for the main interface.]

It is conceived that the VLBI Terminal will be:

- subject to testing,
- interrogated as part of fault diagnosis,
- undergo hardware maintenance,
- undergo perfective and corrective software maintenance (for example updating of a configuration file or updating of the operating system).

Test, diagnostics and maintenance is not the primary goal of this interface. Additional interfaces (for example remote access engineering interfaces between the workstation of an engineer, or maintainer and the VLBI Terminal) are used to facilitate remote maintenance, test and diagnostics.

Having said that, design features required for diagnosis and maintenance that are provided by the Telescope and Accelerator Controlled with Objects (TACO) Next Generation Objects (TANGO) framework are:

a) Support for fault diagnosis by supporting drill-down (inspection), allowing a client to navigate from one device to another, up or down the hierarchy TANGO devices.
b) Perfective and corrective maintenance of the interface software is supported by the broker, making the design extensible in terms of adding and removing TANGO devices. Addition/removal of TANGO attributes to/from a device affects only the existing TANGO facility database and specific clients that consider the semantics of the specific attributes in their logical implementation.
c) System maintenance often involves replacement of faulty equipment with serviceable one. Many equipment are represented by TANGO devices.

Refer to section 6 for the topic of interface testing, and how the TANGO framework facilitates it.

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4 Safety Aspects

[Safety aspects of interfaces arise from application of the safety provisions of the SKA Product Assurance & Safety Plan SKA-OFF.PAQA-SKO-QP-001, such as the mandatory Safety Assessment. In addition to the products of the Safety programme, safety critical interfaces shall be highlighted in ICDs as in any other design or operations related documents.]

No safety aspects have been identified for this interface, as it specifies a Data Exchange interface which carries no safety-related information.

Note that safety concerns related to lasers are addressed by the ICD TM to SaDT, [RD1].

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5 I.S1M.TM_VLBI.001: TM MID to VLBI Terminal MID Interface

This section specifies all the interface implementation details of the data exchange interface S1M.TM_VLBI.001.

The section contains sub-sections that describe this interface in terms of:

a) section 5.1: intention,
b) section 5.2: topology,
c) section 5.3: OSI representation,
d) section 5.4: required throughput,
e) section 5.5: implementation.

This interface is made up of the following classes:

- Data exchange (protocol stack).

5.1 Interface Intention

The scope of this interface is data exchange between TM MID and the VLBI Terminal related to enable:

- Set-up of VLBI Terminal for VLBI experiments that the SKA1 MID Telescope participates in,
- Monitoring of VLBI Terminal,
- TM sending metadata to VLBI Terminal.

Figure 1 shows high level interactions between TM and VLBI Terminal using a scenario in which a VLBI observation is started, as a swimlane diagram. Figure 2 shows interactions for a scenario in which a VLBI observation runs to completion.

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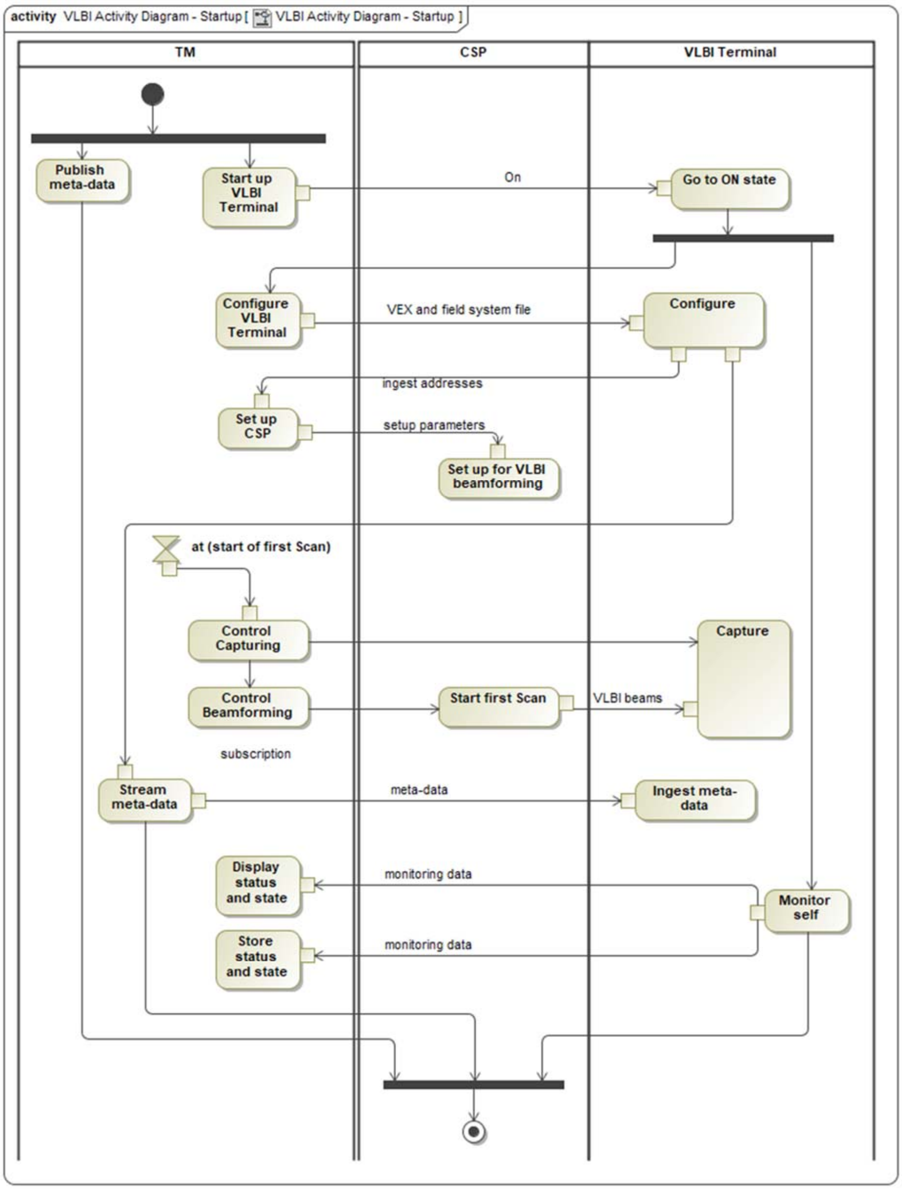

Figure 1: Interface Activity Diagram - Start-up

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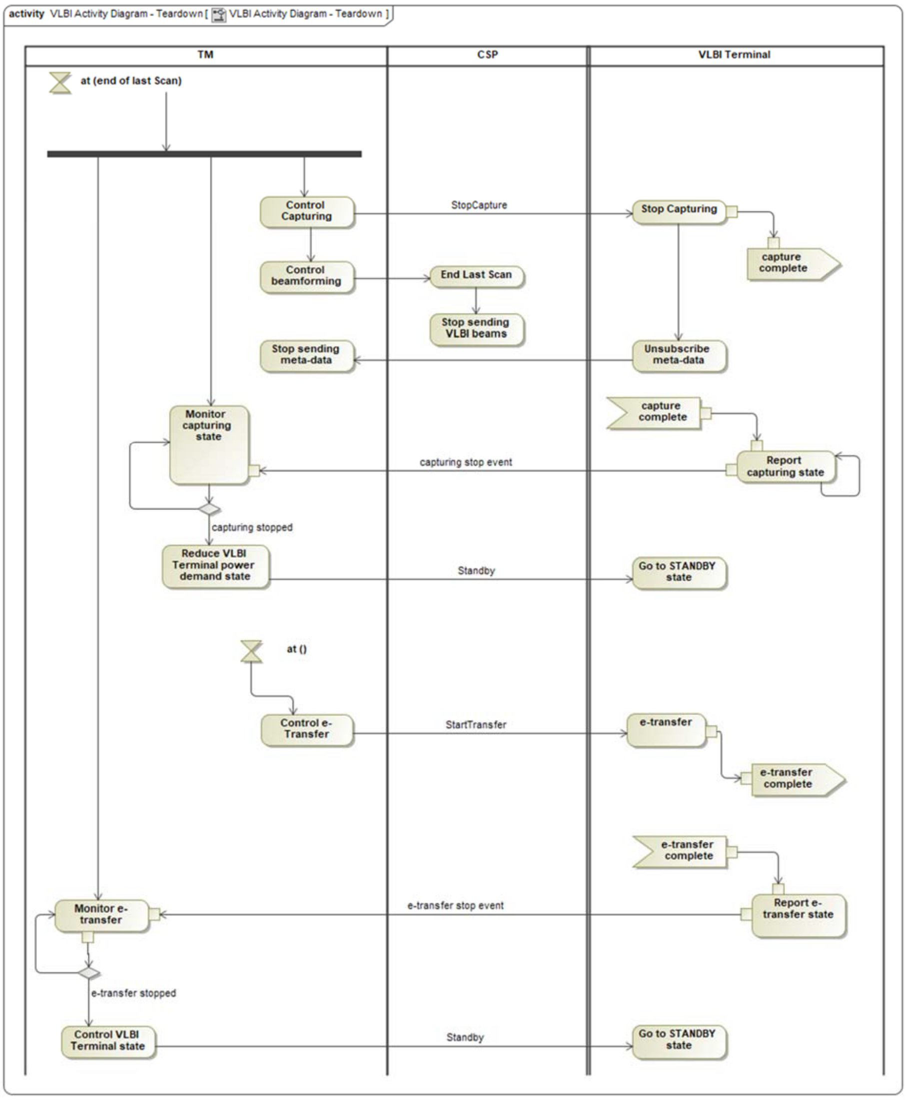

Figure 2: Interface Activity Diagram - Teardown

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5.2 Interface Topology

This data exchange interface uses the SaDT Non-Science Data Network and SDP to provide lower Open Systems Interconnection (OSI) communication layers (refer to [RD6]). The TM MID interface to SaDT is I.S1M.TM_SaDT.003 (refer to [RD1]). The MID VLBI Terminal interface to the SDP MID is I.S1M.SDP_VLBI.TBD (refer to [RD16]). The MID SDP interface with MID SaDT is I.S1M.SaDT_SDP.001 (refer to [RD15]). These relationships between I.S1M.TM_VLBI.001 and the interfaces with SaDT and SDP are shown in Figure 3.

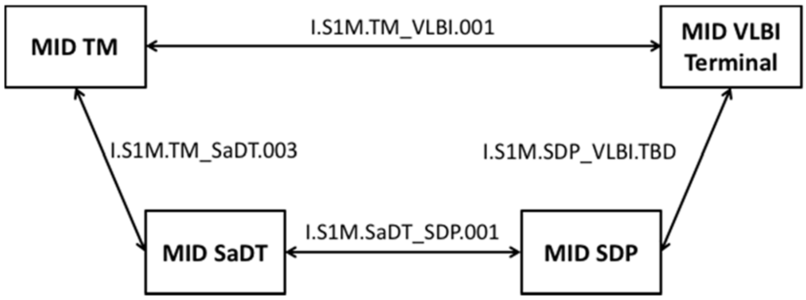

Figure 3: Interface Topology

5.3 OSI Layer Representation of TANGO Interface

This section describes, for information, the implementation in terms of layers of the OSI model.

a) Application Layer:
   i. TANGO - states, list of messages types and grammar are described in TANGO User Manual [RD6], and its application in this interface, as described in section 5.5.
b) Presentation Layer:
   i. Internet inter-ORB Protocol (IIOP), part of the Common Object Request Broker Architecture (CORBA) standard [RD7],
   ii. ØMQ [RD8],
   iii. Endianness: Little Endian.
c) Session Layer:
   i. IIOP, part of the CORBA standard [RD7],
   ii. ØMQ [RD8].
d) Transport layer:
   i. Transmission Control Protocol, RFC 793 [AD4] and related suite of standards and recommendations.
e) Network Layer:
   i. Internet Protocol v6 [AD5].
f) Data Link Layer:
   i. Refer to TM to SaDT ICD [RD1],
   ii. Refer to SaDT MID to SDP MID ICD [RD15].
g) Physical Layer:
   i. Refer to TM to SaDT ICD [RD1],
   ii. Refer to SaDT MID to SDP MID ICD [RD15].

5.4 Required Throughput

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To support S1M.TM_VLBI.001, the transportation layer will be implemented by SaDT (see [RD1]). The connection will be between two physical points (one for TM MID and one for VLBI Terminal).

The estimated required data throughput will be:

a) TM MID to VLBI Terminal: 1 Gbps TBC01,
b) VLBI Terminal to TM MID: 1 Gbps TBC02.

The above maximum throughput is from calculations, based on the interface implementation in sub-section 5.5 and assumptions about metadata required by the VLBI Terminal and assumptions about VLBI Terminal sizing.

5.5 Interface Implementation

This sub-section describes the interfaces (common device aspects being described in one paragraph, which is followed by a paragraph for each specific TANGO device), and the data that flow between them.

Below are three interface diagrams, each showing interfacing components (products of the Product Breakdown Structure (PBS), TANGO clients, TANGO devices, etc.) and protocols for flows of different kinds of information between the TM and the VLBI Terminal. The focus areas of the different diagrams are:

a) Figure 4: TANGO commands and attribute events[1],
b) Figure 5: TANGO archive events,
c) Figure 6: logs.

[1] Note that the hierarchy of TANGO devices shown in Figure 4 is not a strict topology for command and attribute event propagation, but rather shows TANGO devices that operate on monitoring and control information of different levels of abstraction (summarised/abstract at the top, while for the bottom layers it's detailed and closely coupled to the equipment that are represented by the TANGO devices). The different levels of abstraction may in some cases manifest as TANGO devices representing some items at different tiers in the PBS.

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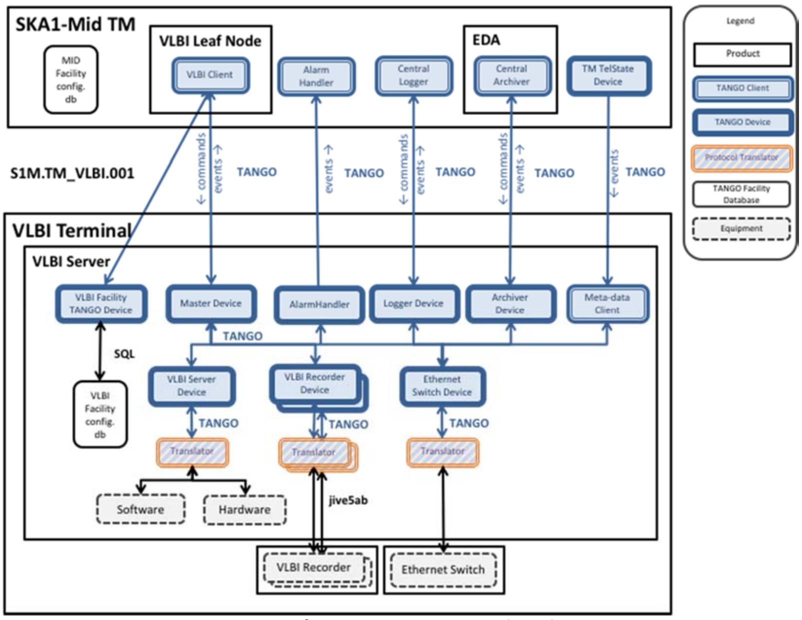

Figure 4: Interface Diagram - Commands and Events

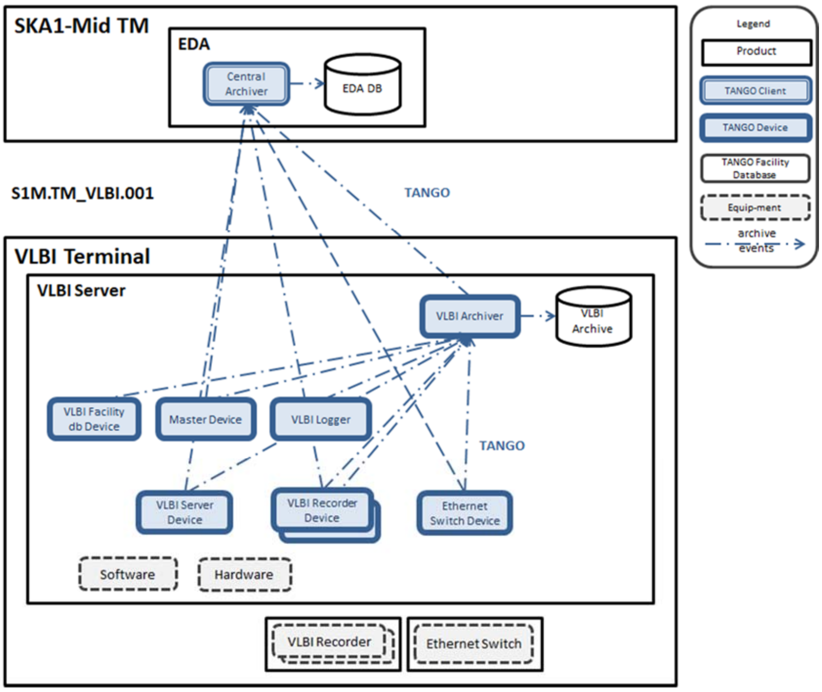

Figure 5: Interface Diagram - Archiving

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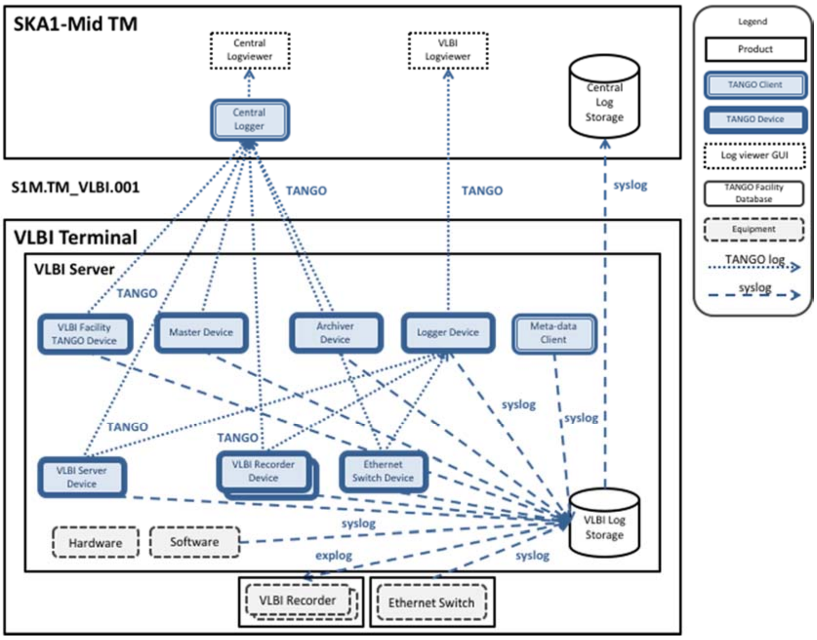

Figure 6: Interface Diagram - Logging

5.5.1 TANGO Facility Context

There are two contexts in which conversations between TM and the VLBI Terminal take place: the telescope context, and the VLBI Terminal context. These contexts are mapped to TANGO facilities. The details of the configuration databases of these facilities are given below.

5.5.1.1 SKA_MID Facility Database

The details of the SKA_MID telescope facility TANGO configuration database for TM devices and clients are:

a) Host: ska_mid
b) Port: 10000

5.5.1.2 MID_VLBI Facility Database

The details of the MID_ VLBI element facility TANGO configuration database to access the VLBI Terminal Master, Logger, Alarm Handler, Archiver (higher level) Devices and (lower level) devices that are part of the MID_VLBI facility (Server, Recorder, Ethernet Switch) are:

a) Host: mid_vlbi
b) Port: 10000

5.5.2 TANGO Device Interfaces – common aspects

This sub-section describes common aspects of TANGO devices of this interface.

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The interface is between a TANGO [RD10] client and a TANGO device server. The TANGO device server exposes TANGO attributes and commands via the interface to clients.

The client uses requests to read or write TANGO device attributes, and to invoke TANGO device commands. Synchronous communication relating to TANGO device attributes and commands are based on the CORBA [RD7] architecture. In the CORBA interaction context, the omniORB is implemented in both VLBI Terminal and TM MID.

Event-based communication (refer [RD10] par. 4.6) is implemented with the ØMQ library (refer [RD12]). The TANGO client is the event subscriber, and the TANGO device server is the event publisher.

5.5.2.1 Device Name

The device name is in accordance with [RD9] par. 4.1.

5.5.2.2 Device Properties

SKA wide properties mandated for devices are found in [RD10] par. 3.

5.5.2.3 Device States

Possible device states are limited by TANGO version 9 to a fixed set. Guidelines for TANGO Device state use for devices are given in [RD12].

5.5.2.4 Commands

Standard TANGO commands are described in [RD10] par. 6.4.2.1 and par. A.7.

SKA project common TANGO commands for SKA Device, as described in [RD10] par. 10.4 apply.

5.5.2.5 Attributes

Standard TANGO device attributes are described in [RD10] par. B.6.

SKA project common TANGO attributes for SKA Device, as described in [RD10] par. 10.4, apply.

5.5.2.6 Events

Implementation of event subscription is described in [RD10] par. 4.6.

Heartbeat mechanism is described in [RD10] par. 7.4.1.
Attribute events identification take [RD10] par. 6.2 as a guideline.

5.5.3 VLBI Master Device Interface

This is the VLBI Terminal device that provides a monitoring gateway to status and state of the VLBI Terminal, and high level commands with which TM needs to control VLBI Terminal.

The TANGO device server exposes TANGO attributes and commands via the interface to clients. The roles of the interfacing systems are:

- TANGO Client: TM MID
- TANGO Device Server: VLBI Terminal

5.5.3.1 Device Name

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The TANGO device name of this device server is `mid_vlbi/elt/master`

5.5.3.2 Device Properties

Specific TANGO Device properties of the VLBI Master Device are:

a) SkaLevel: 1 (refer [RD10] par. 3)
b) ElementLoggerAddress (refer [RD10] par. 10).

5.5.3.3 Device Sates

Specific TANGO Device states that are applicable to the VLBI Terminal Master Device are listed in Table 2. Figure 7 is a state chart for the states of the VLBI Terminal Master Device.

Table 2: VLBI Master Device States

State name	State Description
OFF	VLBI Terminal equipment is not powered.
INIT	VLBI Terminal is initialising. When entering this state from any state other than OFF, the VLBI Terminal will re-initialise.
STANDBY	Low power state in which the VLBI Terminal is not performing it's prime functions, but only support functions like self-monitoring, logging, etc.
ON	VLBI Terminal is operational and either ready to capture and transfer data, or capturing data, or transferring data, or both.
ALARM	The value of an attribute of the device has crossed the alarm threshold.
FAULT	VLBI Terminal critical fault.
UNKNOWN	VLBI Terminal state in not known.

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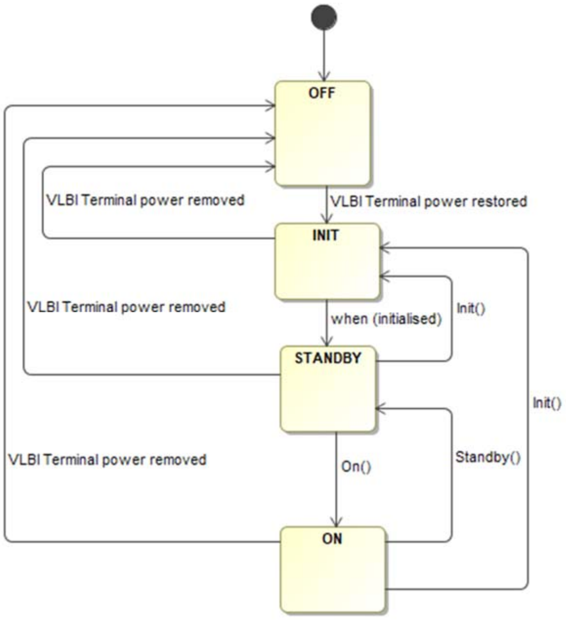

Figure 7: VLBI Terminal State Chart

5.5.3.4 Commands

Specific commands for the VLBI Master Device are provided in Table 3.

Table 3: VLBI Master Device Commands

Name	Input Type	Input Args	Output Type	Display Level	Allowed in states	Description
Init	None	N/A	DevVoid	OPERATOR	STANDBY ON	Triggers transition to the INIT state.
Standby	None	N/A	DevVoid	OPERATOR	ON	Triggers transition to the STANDBY state.
On	None	N/A	DevVoid	OPERATOR	STANDBY	Triggers transition to the ON state.
StartCapture	None	N/A	DevVoid	OPERATOR	ON	Command to start capturing VLBI beams.
StopCapture	None	N/A	DevVoid	OPERATOR	ON	Command to stop capturing VLBI beams.
StartTransfer	None	N/A	DevVoid	OPERATOR	ON	Command to start transferring data.
StopTransfer	None	N/A	DevVoid	OPERATOR	ON	Command to stop transferring data.

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5.5.3.5 *Attributes*

Table 4 lists specific attributes for the VLBI Master Device Server.

The following properties of the attributes of the VLBI Master Device are **TBD08**: unit minimum, maximum, warn level and alarm level.

Table 4: VLBI Master Device Attributes

Name	Attr. Type	Data Type	Read/ Write	Description	Attr. Events
adminMode	Scalar	DevEnum	READ WRITE	Enum. values: ONLINE, OFFLINE, MAINTENANCE, NOT_FITTED, RESERVED	Change: absolute 1 Archive: absolute 1
versionId	Scalar	DevString	READ	Version number of device.	Change: absolute 1 Archive: absolute 1
healthState	Scalar	DevEnum	READ	Enum. values: OK, DEGRADED, FAILED, UNKNOWN	Change: absolute 1 Archive: absolute 1
controlMode	Scalar	DevEnum	READ WRITE	Enum. values: UNRESTRICTED, CENTRAL, LOCAL	Change: absolute 1 Archive: absolute 1
powerState	Scalar	DevEnum	READ	Enum. values: OFF, UPS, LOW, FULL	Change: absolute 1 Archive: absolute 1
elementLogLevel	Scalar	DevEnum	READ	Enum. values: OFF, FATAL, ERROR, WARNING, INFO, DEBUG	Change: absolute 1 Archive: absolute 1
centralLogLevel	Scalar	DevEnum	READ	Enum. values: OFF, FATAL, ERROR, WARNING, INFO, DEBUG	Change: absolute 1 Archive: absolute 1
storageLogLevel	Scalar	DevEnum	READ	Enum. values: OFF, FATAL, ERROR, WARNING, INFO, DEBUG	Change: absolute 1 Archive: absolute 1
synchronised	Scalar	DevBool	READ	Indicates whether the VLBI Terminal is synchronised via NTP or not.	Change: absolute 1 Archive: absolute 1
vlbiRecordernnn[2]	Scalar	DevString	READ	Fully Qualified Domain Name (FQDN) of VLBI Recorder Device nnn.	Change: absolute 1 Archive: absolute 1
vlbiServer	Scalar	DevString	READ	FQDN of the VLBI Server Device.	Change: absolute 1 Archive: absolute 1

[2] *nnn* is a unique number that uniquely identifies a specific VLBI Recorder Device. There will be *nnn* number of VLBI Recorder Fully Qualified Domain Name (FQDN) attributes, one for each VLBI Recorder.

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Name	Attr. Type	Data Type	Read/ Write	Description	Attr. Events
switch	Scalar	DevString	READ	FQDN of the Switch Device.	Change: absolute 1 Archive: absolute 1
fieldSystemFile	Scalar	DevString	READ WRITE	Field system file as a string. WRITE attribute for setting file. READ attribute for showing file in use. Blank if not configured with file.	Change: absolute 1 Archive: absolute 1
vexFile	Scalar	DevString	READ WRITE	VEX file (refer to [RD17]) as a string. WRITE attribute for setting VEX file. READ attribute shows VEX file in use. Blank if not configured with file.	Change: absolute 1 Archive: absolute 1
experimentId	Scalar	DevString	READ	Experiment ID (as defined in the $EXPER block of the VEX file) that the VLBI Terminal is configured for. Blank if not configured for experiment.	Change: absolute 1 Archive: absolute 1
capturing	Scalar	DevBool	READ	True if VLBI terminal is capturing VLBI beams, else false.	Change: absolute 1 Archive: absolute 1
transferring	Scalar	DevBool	READ	True if VLBI terminal is transferring VLBI beams, else false.	Change: absolute 1 Archive: absolute 1

Attributes for:

- reception of metadata status and statistics,
- VLBI beam capturing status and statistics,
- data transferring status and statistics,
- connectedness to CSP (VDIF protocol related),
- connectedness to eVLBI service,
- synchronisation status (NTP).

5.5.3.6 Events

Table 4 lists specific events for the VLBI Master Device against each attribute.

5.5.4 SKA_MID TM TelState Device Interface

This is the TM MID device that provides meta-data to VLBI Terminal. This device will be specific for VLBI meta-data, for each of the sub-arrays supporting VLBI.

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The TANGO device server exposes TANGO attributes and commands via the interface to clients. The roles of the interfacing systems are:

- TANGO Client: VLBI Terminal
- TANGO Device Server: TM MID

5.5.4.1 Device Name

The TANGO device name of this device server is `mid_tm/tel/telstate_vlbi_[1..4]`

5.5.4.2 Device Properties

Specific TANGO Device properties of the TelState Device are:

- SkaLevel: 1 (refer [RD10] par. 3).

5.5.4.3 Device States

Specific TANGO Device states that are applicable to the TM MID TelState Device Server are listed in Table 5.

Table 5: TM MID TelState Device States

State name	State Description
OFF	TM MID TelState is not running.
INIT	TM MID TelState is initialising.
ON	TM MID TelState is operational.
ALARM	The value of an attribute of the device has crossed the alarm threshold.
FAULT	TM MID TelState is experiencing a critical fault.
UNKNOWN	TM MID TelState state is not known.

5.5.4.4 Commands

This device has no specific commands.

5.5.4.5 Attributes

Table 6 lists specific attributes for the TM MID TelState Device Server.

All attributes are READ attributes (the device determines the values of the attributes, and the client can read them, but not change them).

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Table 6: TM MID TelState Device Attributes

Name	Attr. Type	Description	Attr. Events
Tsys System Temperature	Image	Beam channel ID, Tsys pair for each VLBI beam-channel. Unit: K Every 10-30 s or for every scan if shorter for the different VLBI beams channels. At least provide power in the different beam channels. For LOW as there are no noise diodes, the system temperature will be computed using flux density calibrators, during the observations.	Periodic: 30 s per scan
GPS vs PPS	Spectrum	Ideally from the digitizer 1pps, but if not possible from the H maser/phase micro-stepper 1pps. This offset should be provided during the duration of the observation, at least at the beginning and at the end, but preferably for every scan (equivalent to gps-fmout).	per scan
RFI flagging	Image	Static flagging table. Gain settings on scan boundaries.	per scan
Sub-array definition	Spectrum	IDs of Dishes that are part of the Sub-array for every scan. This information is logged in radio observatories as a sanity check for every scan.	per scan
CBF configuration status / Scan	Scalar DevString	CBF configuration status for every scan, expressed as JSON string. This information is logged in radio observatories as a sanity check for every scan.	per scan
Dish pointing status	Spectrum	Array of Dish ID, Dish dishMode attribute value pairs. Antenna pointing status during the scan (tracking/slewing, equivalent to flag and onsource), for each antenna participating in the Sub-array used to produce the tied-array beams, only for MID.	Change: absolute
Noise diode configuration (achieved)	Spectrum	Noise diode status (enabled/disabled) and non real-time noise diode temperatures versus frequency (for each antenna and receiver), for each Scheduling Block, only for MID (for rxg files).	per scan Change: absolute
weather data	Spectrum	Weather data during the observation: temperature (°C), pressure (mbar) and relative humidity (%), at least every 30 seconds, or for every scan if shorter.	Periodic: 30 s per scan
SEFD	Spectrum	Non-real time: System Equivalent Flux Density (SEFD) for each antenna participating in the sub-array used to produce the tied-array beams, for each Scheduling Block, only for MID.	per Scheduling Block Change: absolute
delay tracking and calibration	Image	Geometric delay and calibration residuals for boresight and off boresight (sourcing from SDP) rolled-up and provided as a fifth order polynomial per receptor per Frequency Slice (or LFAA channel) per polarization every 10 seconds. See ISSUE03.	Periodic: 10 s Change: absolute

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Name	Attr. Type	Description	Attr. Events
tropospheric delays per Dish	Spectrum	Tropospheric delays for every antenna in the subarray, every 10-30 seconds, only for MID.	Periodic: 10 s
ionospheric delays per Dish, per Station	Spectrum	Ionospheric delays for every station in the subarray, every 10-30 s, for MID and LOW.	Periodic: 10 s
SDP's polarisation corrections	Spectrum	Polarization corrections used by the beamformer, every 10 s (or agreed latency).	Periodic: 10 s
Receptor or station weights	Spectrum	Receptor or station weights used by the beamformer (telescope model), every 10 sec (or agreed latency).	Periodic: 10 s
Gain curve	Spectrum	Non real-time: Gain curve (4th order polynomial) + DPFU for every antenna participating in the sub-array (for rxg and antabfs files), for each Scheduling Block, only for MID.	Change: absolute

5.5.4.6 Events

Table 6 lists specific events for the TM MID TelState Device against each attribute.

5.5.5 VLBI Logger Device Interface

The TANGO device server exposes TANGO attributes and commands via the interface to clients. The roles of the interfacing systems are:

- TANGO Client: TM MID
- TANGO Device Server: VLBI Terminal

Device name: `mid_vlbi/elt/logger`

5.5.6 VLBI Archiver Device Interface

The TANGO device server exposes TANGO attributes and commands via the interface to clients. The roles of the interfacing systems are:

- TANGO Client: TM MID
- TANGO Device Server: VLBI Terminal

Device name: `mid_vlbi/elt/archiver`

Device properties:

a) SkaLevel: 1 (refer [RD10] par. 3)

5.5.7 VLBI Alarm Handler Device Interface

The TANGO device server exposes TANGO attributes and commands via the interface to clients. The roles of the interfacing systems are:

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- TANGO Client: TM MID
- TANGO Device Server: VLBI Terminal

Device name: `mid_vlbi/elt/handler`

Device properties:

a) SkaLevel: 1 (refer [RD10] par. 3)

5.5.8 VLBI Server Device Interface

The TANGO device server exposes TANGO attributes and commands via the interface to clients. The roles of the interfacing systems are:

- TANGO Client: TM MID
- TANGO Device Server: VLBI Terminal

Device name: `mid_vlbi/elt/server`

Device properties:

a) SkaLevel: 2 (refer [RD10] par. 3),
b) communication parameters needed by the device to communicate to VLBI Server equipment.

Device states: TBD10

Device commands: TBD10

Device attributes: TBD10

5.5.9 VLBI Recorder Device Interface

The TANGO device server exposes TANGO attributes and commands via the interface to clients. The roles of the interfacing systems are:

- TANGO Client: TM MID
- TANGO Device Server: VLBI Terminal

Device name: `mid_vlbi/elt/recordernnn`[3]

Device properties:

a) SkaLevel: 2 (refer [RD10] par. 3),
b) communication parameters needed by the device to communicate to VLBI Recorder equipment.

Device states: TBD11

Device commands: TBD11

Device attributes: TBD11

[3] *nnn* is a unique number that uniquely identifies a specific VLBI Recorder Device.

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5.5.10 VLBI Ethernet Switch Device Interface

The TANGO device server exposes TANGO attributes and commands via the interface to clients. The roles of the interfacing systems are:

- TANGO Client: TM MID
- TANGO Device Server: VLBI Terminal

Device name: `mid_vlbi/elt/switch`

Device properties:

a) SkaLevel: 2 (refer [RD10] par. 3),
b) communication parameters needed by the device to communicate to VLBI Switch equipment.

Device states: TBD12

Device commands: TBD12

Device attributes: TBD12

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6 Interface Verification

6.1 Interface Verification Scope

Syntax checking is limited to ensuring that property, attribute and command naming and minimum, maximum, warning and alarm values are implemented as per the interface implementation section of the ICD. Because both sides of the interface must be implemented from an existing, mature TANGO code base (and therefore regarded as low risk), special measures are not taken to verify that the syntax implementation complies with TANGO documentation (refer to [RD6] and [RD9]).

Interface verification is limited to verification of the behaviour of the interfacing telescope sub-systems which is part of the suite of protocols employed by the TANGO framework. Other specified behaviour of the TM and VLBI Terminal is verified as part of verification of the TM and the VLBI Terminal, as per their test specifications (refer to [RD18], [RD19] and ***TBD VLBI Terminal Test Specification***).

6.2 Interface Verification Stages

The Interface verification process occurs in at least the stages described in Table 7, with identification of responsibilities[4] for verification activities in each stage.

Table 7: Verification Stages

Stage name	Stage Description
Review	Verification of the ICD through formal reviews during the design of the interface. This stage is the responsibility of the leading party in collaboration with the SKA Office, using models and analysis.
Standalone	Verification of the interface implementation of individual sub-systems during their design qualification phase by means of exercising the interface with the use of test equipment and/or simulators. This is the responsibility of the SKA System Team(s) with the support of the Development Team(s).
Integration	Verification of the interface during integration of the interfacing elements, as part of system integration testing. This verification is the responsibility of the system Assembly, Integration and Verification team, with support from the leading and following party Development Team(s). This stage has two phases – an informal verification made at telescope sub-system level in isolation, followed by a carefully controlled sequence of making and verifying made interfaces as part of integration.

[4] The SKA1 Interface Management Plan lays the responsibility for verification at the level of integration of the interfacing systems ("involving the interface being made") on the leading interface party [AD1]. In contrast with that, the SKA1 TM Verification Plan [RD20], Integration and Verification Plan for SKA1_LOW [RD21] and Integration and Verification Plan for SKA1_MID [RD22] lay the responsibility for telescope integration verification on the Assembly Integration and Verification (AIV) Contractor, with the telescope sub-system contractor providing support to them. The responsibilities indicated in this section are in accordance with the latter.

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6.3 Interface Verification Methods

The interface verification methods defined in Table 8 (taken from [RD20]) are used.

Table 8: Verification Methods

Method name	Method Description
Demonstration	Operation of the system, subsystem or a part of the system that relies on observable, functional operation. Instrumentation or other special test equipment may be required to demonstrate functional operation.
Inspection	Visual examination of physical characteristics of system components, visual verification of conformance to documentation, visual verification of conformance to workmanship requirements, visual check or review of project documentation such as software version descriptions, computer source code, and so on. Inspection could include the inspection of design documentation to verify that (typically) non-functional requirements are met.
Test	Operation of the system, subsystem or a part of the system using instrumentation or other special test equipment to collect data for analysis or review. These tests can be performed at any level of assembly within the system hierarchy. The analysis of data derived from tests is an integral part of the test program and should not be confused with 'analysis' defined as follows.
Analysis	Processing of accumulated data obtained from other verification methods. Examples are reduction interpolation or extrapolation of test results. Analysis techniques include systems engineering analysis, statistics, qualitative analysis, analogue modelling, similarity and simulation.

6.4 Verification Cross Reference Matrix

Table 9 briefly describes the proposed verification of interface aspects, identifying the verification method and verification stage in each case.

Table 9: Verification Cross Reference Matrix

Aspect	Description	Stage	Method
Documentation	Review the ICD against telescope functional analysis ([RD3], [RD2]), SKA Control System Guidelines ([RD10]) and the requirement specifications of interfacing sub-systems.	Review	Inspection
TANGO device	Review XML file (generated with TANGO's Pogo utility) against the ICD.	Review	Inspection
TANGO database	Interrogate the TANGO database, using TANGO's Jive utility, ensuring that it is configured for device servers and devices as per the ICD sections that describe the TANGO devices.	Standalone	Demonstration

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Aspect	Description	Stage	Method
TANGO device & device server	Use the ATK Panel from TANGO's Jive utility, and ensure that the following are as per ICD sections that describe TANGO devices: states, properties, commands, attributes.	Standalone	Demonstration
TANGO client	Ensure the client displays typical standard TANGO attribute values and invokes standard TANGO commands against devices as described in the ICD sections that describe TANGO devices.	Standalone	Demonstration
TANGO client	Run the system that implements the client against the system that implements the TANGO database and devices. Ensure that the client can connect to the TANGO database and device servers, invoke commands of devices and receive attribute value events.	Integration	Demonstration
TANGO database, devices & device servers	Run the telescope sub-system that implements the TANGO database and devices against the system that implements the client. Ensure that the client can connect to the TANGO database and device servers, that the devices behave as per invoked commands and that attribute events are received as per subscription.	Integration	Demonstration
ElementLogger	Connect TANGO's LogViewer utility to the telescope sub-system that implements the ElementLogger, and ensure that logs are received.	Standalone	Demonstration
ElementLogger	Connect a rsyslog/Elasticsearch server to the VLBI Terminal, which implements the ElementLogger, and ensure that logs are received.	Standalone	Demonstration
ElementLogger	Connect the TM to the VLBI Terminal, which implements the ElementLogger, and ensure that logs are received.	Integration	Demonstration
OSI[5] layers 1 & 2	For verification of the physical, data link and network layers of the data exchange interface, refer to [RD1] and [RD15].	-	-

[5] OSI layers 3 to 7 (addressed in the interface implementation section of this ICD) verification is covered by the entries in this table.

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7 Notes

7.1 List of TBDs, TBCs and Issues

TBDs and TBCs are specifically listed in Table 10.

Table 10: TBDs and TBCs

Number	Description	Status	Comments
TBD01	Interface following party & point of contact.	Resolved	Resolution: Following party is SKAO, represented by the VLBI Scientist.
TBD02	Interface number and ICD for the interface between VLBI Terminal &SADT.	Resolved	
TBD03	Estimated data throughput from TM MID to MID VLBI Terminal.	Resolved	Plan: For System CDR: VLBI Scientist makes ball park estimate. Resolution: 1 Gbps is estimate for System CDR.
TBD04	Estimated data throughput from MID VLBI Terminal to TM MID.	Resolved	Plan: For System CDR: VLBI Scientist makes ball park estimate. Resolution: 1 Gbps is estimate for System CDR.
TBD05	TelState Device: device properties.	Resolved	Resolution: refer par. 5.5.4.2.
TBD06	VLBI Master Device: device properties.	Resolved	Resolution: refer par. 5.5.3.2.
TBD07	TelState Device: attributes' properties.	Resolved	Resolution: TM Consortium populated, based on VLBI Scientist's presentation.
TBD08	VLBI Master Device: attributes' properties.	**Unresolved**	Plan: TM Consortium provide after System CDR.
TBD09	VLBI Master Device: commands.	Resolved	Resolution: TM Consortium suggested, and following party reviewed.
TBD10	VLBI Server Device: states, commands and attributes.	**Unresolved**	Plan: VLBI Scientist to provide when design of VLBI Terminal matured.
TBD11	VLBI Recorder Device: states, commands and attributes.	**Unresolved**	Plan: VLBI Scientist to provide when design of VLBI Terminal matured.
TBD12	VLBI Ethernet Switch Device: states, commands and attributes.	**Unresolved**	Plan: VLBI Scientist to provide when design of VLBI Terminal matured.

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Number	Description	Status	Comments
TBC01	Estimated throughput: TM MID to MID VLBI Terminal.	**Unresolved**	Plan: For Bridging Activities: TM Consortium estimates, with assumptions about metadata before System CDR.
TBC02	Estimated throughput: MID VLBI Terminal to TM MID	**Unresolved**	Plan: For Bridging Activities: TM Consortium estimates, with assumptions about metadata before System CDR.

7.2 List of Issues

Table 11 contains a list of open and resolved regarding the interfaces described in this ICD.

Table 11: List of Issues

Number	Description	Status	Comments
ISSUE01	Metadata (TelState Device attributes) not defined in detail.	**Unresolved**	Plan: Refine metadata (TelState Device attributes), it with telescope state information as found in SDP to TM ICDs post system CDR.
ISSUE02	Document addresses TM MID to VLBI Terminal interface only.	**Unresolved**	Plan: TM Consortium to address LOW as well as MID in ICD as part of SKA Bridging activities.
ISSUE03	Flow of calibration residuals, and responsibility for generation (SDP is assumed) are still not clear.	**Unresolved**	Plan: TM Consortium and SKAO to resolve through SDP work towards CDR.

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ANNEX 2.4 LOW Signal and Data Transport (SaDT) to VLBI ICD

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INTERFACE CONTROL DOCUMENT
SADT TO VLBI (LOW)

Document Number	100-000000-XXX
Document Type	ICD
Revision	B
Author	C. Brown
Date	2018-11-23
Document Classification	FOR PROJECT USE ONLY
Status	Draft

SQUARE KILOMETRE ARRAY

Name	Designation	Affiliation	Signature
Owned by:			
C. Brown	SaDT System Engineer	SaDT Consortium	
Released by:			
Approved by:			

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DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2018-10-02	-	First draft
B	2018-11-23		Added VLBI Consortium comments

DOCUMENT SOFTWARE

	Package	Version	Filename
Word Processor	MS Word	2018	100-000000-XXX-SADTtoVLBI_LOW_ICD.docx
Block diagrams			
Other			

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington, Macclesfield Cheshire SK11 9DL Registered in England & Wales Company Number: 07881918
Website	www.skatelescope.org

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TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF TABLES

LIST OF FIGURES

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LIST OF ABBREVIATIONS

AD	Applicable Document
CI	Configuration Item
CSP	Central Science Processor
DDBH	Digital Data Back Haul
ESD	Electrostatic Discharge
FEC	Forward Error Correction
GBASE	Gigabit/Second Baseband
GE	Gigabit Ethernet
ICD	Interface Control Document
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organisation for Standardisation
LC	Little Connector
MAC	Media Access Code
M&C	Monitor and Control
MPO	Multi-fibre Push-On
MTU	Maximum Transmit Unit
NSDN	Non-Science Data Network
OM4	Optical Multimode 4
OSI	Open Systems Interconnection model (ISO/IEC 7498-1)
PTP	Precision Time Protocol
QSFP	Quad Small Form factor Pluggable
RD	Reference Document
RFI	Radio Frequency Interference
Rev	Revision
SADT	Signal and Data Transport
SAT	Synchronisation and Timing
SDP	Science Data Processor
SFF	Small Form Factor
SFP	Small form-factor pluggable
SKA	Square Kilometre Array
SKA1	Phase 1 of the SKA
SKA1-Mid	Mid frequency array of dishes of SKA1
TBC	To be confirmed
TBD	To be decided
TM	Telescope Manager
UDP	User Datagram Protocol
VLBI	Very Long Baseline Interferometry

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

1 INTRODUCTION

1.1 Purpose

This Interface Control Document (ICD) defines the exchanges for each of the SADT Consortium led interfaces identified between the SADT Element and the VLBI Element for the SKA1-LOW Telescope. The VLBI Element is comprised by the VLBI Terminal described in [RD2].

1.2 Scope

This ICD aggregates all of the identified inter-element interfaces between the Signal and Data Transport (SADT) Element and the Very Long Baseline Interferometry (VLBI) Element where the SADT Consortium has been identified as the Interface Lead.

1.3 Boundaries of responsibilities

The SKA Office is the Owner of the SADT Element interfaces, and acts as the authority of the system architecture. The point of contact of the Owner is SKA Office Element System Engineer - SADT.

The roles and responsibilities of the element consortia for the SADT led interfaces are as follows:

Party:	SKAO
Point of contact:	SaDT/LOW System Engineer
Role:	Interface Leading Party
Responsibilities:	Drive the definition of the ICD
	Submit the ICD for review and approval

Party:	VLBI Consortium
Point of contact:	SKA VLBI Scientist
Role:	Interface Following Party
Responsibilities:	Assist with the definition of the ICD
	Review the ICD
	Approve the ICD

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2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

[AD1] SKA-TEL-SKO-0000008, “SKA Phase 1 Systems Requirements Specification”

[AD2] SKA-TEL-SKO-0000740, Rev 01, “SKA Project Safety Management Plan”

2.2 Reference documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD1] 300-000000-023 “SADT to CSP Interface Control Document”

[RD2] SKA-TEL-SKO-0000116, “SKA1 External VLBI Interface Control Document”

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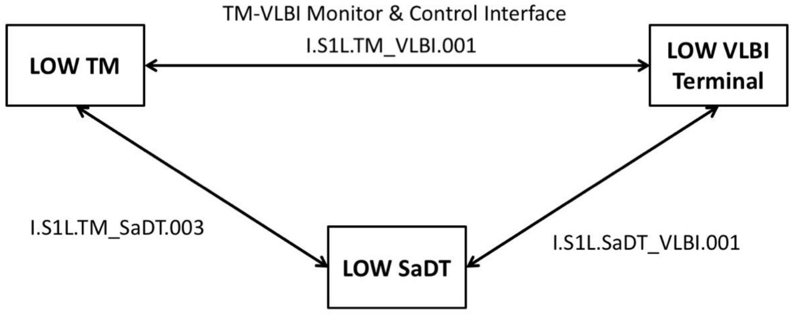
3 INTERFACE DEFINITION

This Interface Control Document (ICD) describes the interfaces between SADT and VLBI Element that are allocated within the SKA1-LOW Telescope. The VLBI Element [RD2] interfaces to two (2) SADT sub-elements:

- SADT.NSDN – provision for Monitor and Control, and NTP services for VLBI.
- SADT.CSP-SDP – provision for transport of science data to VLBI.



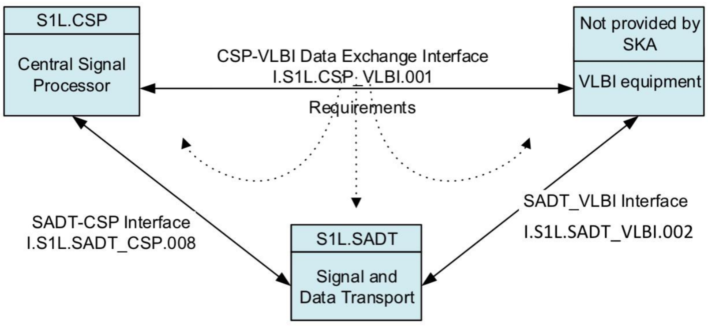


Figure 1. SADT-VLBI LOW ICD Topology (top SADT.NDSN; bottom SADT.CSP-SDP)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

3.1 Interface Identification

Unique identifiers are prescribed for each of the interfaces pertinent to the SADT-VLBI ICD; the methodology imposed shall permit the immediate identification of any given interface, and following the underlying logic:

I.S1T.xxxx_yyyy.nnn.ccc

Where periods are used as separators and digits are defined as follows:

I	Defines the item as an interface
S	Defines that the item pertains to the SKA Project
1	Defines the item as being current at Phase 1†
T	Defines whether the item pertains to the Telescope (T), MID (M) or LOW (L)
xxxx	Defines the interfacing element 1 (lead)‡
yyyy	Defines interfacing element 2 (non-lead)‡
nnn	A unique number string between 001 and 999
ccc	Text describing the data

Notes:

† Subsequent numbering/lettering to be used as appropriate for progressive project phases.

‡ A list of suitable element acronyms are tabulated (Table 1):

Interface No.	SADT Product ID	VLBI Product ID	Interface Description
I.S1L.SADT_VLBI.001	**NSDN** 142-000000	**VLBI Terminal** CIN (TBD.001)	Local Monitor and Control (LMC)
I.S1L.SADT_VLBI.002	**CSP-SDP** 146-000000	**VLBI Terminal** CIN (TBD.001)	VLBI Science Data (VLBI)

Table 1. SADT-VLBI Interface Identification

For example:

I.S1L.SADT_VLBI.001

Defines an interface (I) belonging to the SKA project (S), current under phase 1 (1), specifically to SKA1-Low (L), where SADT element is lead (SADT) and interfaces with the VLBI Element (VLBI), and the specific interface is number 001.

In this ICD each interface will be identified, its constituents clearly and qualitatively described and fundamental requirements and specifications shall be disclosed. And finally, be supplemented by the element's respective Product Name and Configuration Item (CI) number, in the following manner:

- **Signal and Data Transport** – 105-000000
- **CSP Correlator and Beamformer** – 111-000000

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3.1.1 I.S1L.SADT_VLBI.001

Interface is between the **Non-Science Data Network** and **VLBI Element**, and facilitates data exchange relating to non-science data, typical network infrastructure services, and monitor and control functions to Telescope Manager.

3.1.2 I.S1L.SADT_VLBI.002

Interface is between the **CSP-SDP** and **VLBI Element**, and facilitates data exchange relating to "VLBI" science data which has been processed by the Central Signal Processor (CSP).

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4 SAFETY ASPECTS

Safety aspects of interfaces arise from application of the safety provisions of the SKA Project Safety Management Plan [AD1], such as the mandatory Safety Assessment. In addition to the products of the Safety programme, safety critical interfaces shall be highlighted in ICDs as in any other design or operations related documents.

The optical components of the 10GE and 100GE links will use Laser Class 1 (or 1M) devices as described in IEC60825-1. Suitable labels warning about exposure will be attached. Optical modules such as SFP+ (10GBASE-LR) (10GBASE-LR), QSFP28 and long-haul optics are ESD class 2 and normal handling precautions should be observed to prevent damage from electrical discharges. The following table (Table 2) applies to interfaces:

- I.S1L.SADT_VLBI.001
- I.S1L.SADT_VLBI.002

No.	Title	Requirement
S.R.1	Optical components	Laser Class 1
S.R.2	Laser safety	Labels must be attached
S.R.3	SFP+	ESD class 2 (Line side is manufacturer specific)
S.R.4	QSFP28 modules	ESD class 2 (Line side is manufacturer specific)
S.R.5	ESD protection	Handling precautions as per manufacturer recommendations
S.R.6	Optical Modules (SFP+ (10GBASE-LR) (10GBASE-LR), QSFP28 & long-haul optics)	Modules must be carefully and correctly seated into switching and long haul equipment, as described in manufacturer's instructions.
S.R.7	Cabling	Cables/Fibres to Switch Ports must be dressed into cable holders, both horizontally and vertically.
S.R.8	Unused optical interfaces	Unused optical interfaces on switch/long haul equipment must be closed using rubber plugs, for safety and environmental ingress protection.
S.R.9	Safety Standards	Safety standards as per industry "good practice."

Table 2. Safety Requirements

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5 INTERFACE IMPLEMENTATION SPECIFICATION

5.1 I.S1L.SADT_VLBI.001

Specifications are identified in Table 3

Specification Title	Verification ID	Specification
Interface Demarcation (SADT Product)	VER-100-xxx-001	**SPC_Core_Router** (CIN 142-054000) **QSFP28_Pluggable_Modules** (CIN 146-047000) (Terminating with 1 "Electrical Ends")
Interface Demarcation (VLBI Product)	VER-100-xxx-002	**VLBI Terminal** (CIN TBD.001) (Terminating with 1 **QSFP28 Transceiver Sockets**)
Mechanical Specification		
Optical Connectors	VER-100-xxx-003	SADT: **QSFP28_Pluggable_Module** VLBI: **QSFP28 Transceiver Socket**
SADT Interface Item	VER-100-xxx-004	One (1) instances of **QSFP28_Pluggable_Modules**
VLBI Interface Item	VER-100-xxx-005	One (1) instances **QSFP28 Transceiver Sockets**
Cabling Client-side	VER-100-xxx-006	SADT Provides all cable routing and management
Interfacing Item Proximity	VER-100-xxx-007	Distance between **SPC_Core_Router** and **VLBI Terminal** shall not exceed 30m, and shall, if possible reside in adjacent racks in the Science Processing Centre/Facility.
Electrical, Electronic and Electro-optical Specification		
Pluggable Modules	VER-100-xxx-008	**QSFP28_Pluggable_Modules** shall meet 4x25G Electrical I/O CAUI-4 and IEEE 802.3-2015
Power Specification		
Power: **QSFP28_Pluggable_Modules**	VER-100-xxx-009	VLBI shall provide 2.5 Watts DC for each instance of **QSFP28_Pluggable_Module** with power and connections defined in MSA SFF-8679, QSFP28 4X Base Electrical Specification.
Data Transport/Exchange Specification		
Wire Data Rate Across Interface	VER-100-xxx-010	100 Gbit/sec maximum physical links capacity
Data Link and Framing (OSI L2)	VER-100-xxx-011	As per Ethernet IEEE 802.3-2015 (with Jumbo frames IP MTU 9000 bytes)
Client-Side Link Capacity	VER-100-xxx-012	100Gbit/sec (as per Ethernet IEEE 802.3-2015) for 100GBASE-SR4†
Forward Error Correction (FEC)	VER-100-xxx-013	Mandatory, as defined in IEEE 802.3-2015
Data Traffic Profile	VER-100-xxx-014	Bidirectional data flow.
Client-Side Link Load	VER-100-xxx-015	<80% Occupancy (total capacity) for each 100Gbit/sec link (**TBC**) but may operate at 100% capacity for peak load periods.
Flow control	VER-100-xxx-016	Provided by SADT NSDN equipment
Data buffering	VER-100-xxx-017	Buffering will support multiple classes of traffic.
Transport latency	VER-100-xxx-018	SADT equipment provides minimum latency
Packet Loss	VER-100-xxx-019	SADT provides $<7\times10^{-8}$ MAC layer, $<7\times10^{-11}$ with FEC 10^{-12} equivalent MAC BER, 10^{-15} with FEC (IEEE 802.3ba) [RD12]
Packet Out-of-Order	VER-100-xxx-020	No packets out of order (SADT provides point to point links)
Traffic Shape	VER-100-xxx-021	Bursty
Nested Header	VER-100-xxx-022	Supported
Packet Structure (pluggable interface)	VER-100-xxx-023	Ethernet/IP/TCP/Application Header/Data and Ethernet/IP/UDP
IP Internet Layer (OSI Layer 3)	VER-100-xxx-024	IPv4 RFC 791, and support IPv6 RFC 2460
Transport Layer	VER-100-xxx-025	TCP, UDP and multicast are available
Ethernet Swiching	VER-100-xxx-026	Provided by SaDT

Table 3. I.S1L.SADT_VLBI.001 Interface Implementation

† Different flows on four components making up QSFP28 electrical interface not acceptable.

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5.2 I.S1L.SADT_VLBI.002

Specifications are identified in Table 4

Specification Title	Verification ID	Specification
Service Description	N/A	**VLBI Science Data** (**VLBI**)
Interface Demarcation (SADT Product)	VER-100-xxx-001	**QSFP28_Pluggable_Modules** (CIN 146-047000) (Terminating with 1 "Electrical Ends")
Interface Demarcation (VLBI Product)	VER-100-xxx-002	**VLBI Terminal** (CIN TBD.001) (Terminating with 1 **QSFP28 Transceiver Sockets**)
	Mechanical Specification	
Optical Connectors	VER-100-xxx-003	SADT: **QSFP28_Pluggable_Module** VLBI: **QSFP28 Transceiver Socket**
SADT Interface Item	VER-100-xxx-004	One (1) instances of **QSFP28_Pluggable_Modules**
VLBI Interface Item	VER-100-xxx-005	One (1) instances **QSFP28 Transceiver Sockets**
Cabling Client-side	VER-100-xxx-006	SADT Provides all cable routing and management
Interfacing Item Proximity	VER-100-xxx-007	The **Muxponder** and **VLBI Terminal** shall, if possible, reside in a shared rack or within adjacent racks in the Science Processing Centre/Facility.
	Electrical, Electronic and Electro-optical Specification	
Pluggable Modules	VER-100-xxx-008	**QSFP28_Pluggable_Modules** shall meet 4x25G Electrical I/O CAUI-4 and IEEE 802.3-2015
	Power Specification	
Power: **QSFP28_Pluggable_Modules**	VER-100-xxx-009	VLBI shall provide 2.5 Watts DC for each instance of **QSFP28_Pluggable_Module** with power and connections defined in MSA SFF-8679, QSFP28 4X Base Electrical Specification.
	Data Transport/Exchange Specification	
Wire Data Rate Across Interface	VER-100-xxx-010	100 Gbit/sec maximum physical links capacity
Data Link and Framing (OSI L2)	VER-100-xxx-011	As per Ethernet IEEE 802.3-2015 (with Jumbo frames IP MTU 9000 bytes)
Client-Side Link Capacity	VER-100-xxx-012	100Gbit/sec (as per Ethernet IEEE 802.3-2015) for 100GBASE-SR4†
Forward Error Correction (FEC)	VER-100-xxx-013	Mandatory, as defined in IEEE 802.3-2015
Data Traffic Profile	VER-100-xxx-014	Continuous unidirectional data flow (CSP to VLBI via SADT) Comprising UDP traffic
Client-Side Link Load	VER-100-xxx-015	<80% Occupancy (total capacity) for each 100Gbit/sec link (**TBC**) but may operate at 100% capacity for peak load periods.
Flow control	VER-100-xxx-016	No flow control provided by SADT
Data buffering	VER-100-xxx-017	No data buffering provided by SADT‡
Transport latency	VER-100-xxx-018	SADT equipment provides minimum latency
Packet Loss	VER-100-xxx-019	SADT provides $<7\times10^{-8}$ MAC layer, $<7\times10^{-11}$ with FEC 10^{-12} equivalent MAC BER, 10^{-15} with FEC (IEEE 802.3ba) [RD12]
Packet Out-of-Order	VER-100-xxx-020	No packets out of order (SADT provides point to point links)
Nested Header	VER-100-xxx-021	Implemented for VLBI
Packet Structure (pluggable interface)	VER-100-xxx-022	Ethernet/IP/UDP/Application Header/Science Data
IP Internet Layer (OSI Layer 3)	VER-100-xxx-023	IPv4 RFC 791
Transport Layer	VER-100-xxx-024	UDP RFC 768, Multicast RFC 1112, RFC 4606 (group management), RFC5771 (admin scoped addresses)
Application Header	VER-100-xxx-025	No special action to be taken by SADT, VDIF protocol is an application protocol carried by UDP/IP/Ethernet
Payload	VER-100-xxx-026	No special action to be taken by SADT, VDIF protocol is an application protocol carried by UDP/IP/Ethernet
Physical Layer Monitoring (SADT)	VER-100-xxx-027	SADT Shall monitor Layer 1 and 2 statistics using DOM and SFF-8472 Diagnostic Monitoring Interface for Optical Transceivers (via vendor EMS, SADT.NMGR and TM)
Physical Layer Monitoring (VLBI)	VER-100-xxx-028	VLBI Collect OSI Layer 1 and 2 statistics from Ethernet modules on the CSP-Side of the interface. Access via TM.

Table 4. I.S1L.SADT_VLBI.002 Interface Implementation

‡ No statistical multiplexing within SADT sub-systems which may lead to potential contention.

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6 INTERFACE VERIFICATION

Verification actions are summarised in the following tables:

VER-100-xxx-001		
VER-100-xxx-002		
VER-100-xxx-003		
VER-100-xxx-004		
VER-100-xxx-005		
VER-100-xxx-006		
VER-100-xxx-007		
VER-100-xxx-008		
VER-100-xxx-009		
VER-100-xxx-010		
VER-100-xxx-011		
VER-100-xxx-012		
VER-100-xxx-013		
VER-100-xxx-014		
VER-100-xxx-015		
VER-100-xxx-016		
VER-100-xxx-017		
VER-100-xxx-018		
VER-100-xxx-019		
VER-100-xxx-020		
VER-100-xxx-021		
VER-100-xxx-022		
VER-100-xxx-023		
VER-100-xxx-024		
VER-100-xxx-025		
VER-100-xxx-026		

Table 5. Verification actions (I.S1L.SADT_VLBI.001)

VER ID	Mechanism	Description of activity and responsible party
VER-100-xxx-001		
VER-100-xxx-002		
VER-100-xxx-003		
VER-100-xxx-004		
VER-100-xxx-005		
VER-100-xxx-006		
VER-100-xxx-007		
VER-100-xxx-008		
VER-100-xxx-009		
VER-100-xxx-010		
VER-100-xxx-011		
VER-100-xxx-012		
VER-100-xxx-013		
VER-100-xxx-014		
VER-100-xxx-015		
VER-100-xxx-016		
VER-100-xxx-017		
VER-100-xxx-018		
VER-100-xxx-019		
VER-100-xxx-020		
VER-100-xxx-021		
VER-100-xxx-022		

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VER-100-xxx-023		
VER-100-xxx-024		
VER-100-xxx-025		
VER-100-xxx-026		
VER-100-xxx-027		
VER-100-xxx-028		

Table 6. Verification actions (I.S1L.SADT_VLBI.002)

7 TBD ITEMS

TBDs are summarised in the table below (Table 7):

Item No.	Description	Owner	Required
TBD.001	VLBI Terminal CIN	SKAO	System CDR

Table 7. Summary of TBDs

7.1 Known issues and outstanding items

8 INTERFACE REQUIREMENTS

SADT Req. ID	Requirement

Table 8. SADT Requirements I.S1L.SADT_VLBI.001

SADT Req. ID	Requirement

Table 9. SADT Requirements I.S1L.SADT_VLBI.002

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ANNEX 2.5 MID Signal and Data Transport (SaDT) to VLBI ICD

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

INTERFACE CONTROL DOCUMENT
SADT TO VLBI (MID)

Document Number	300-000000-XXX
Document Type	ICD
Revision	C
Author	C. Brown
Date	2018-11-23
Document Classification	FOR PROJECT USE ONLY
Status	Draft

Name	Designation	Affiliation	Signature
Owned by:			
C. Brown	SaDT System Engineer	SaDT Consortium	
Released by:			
Approved by:			

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DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2018-08-07	-	First draft
B	2018-10-02		Added comments from SKAO/VLBI scientist, generated ICD for LOW
C	2018-11-23		Added VLBI Consortium comments

DOCUMENT SOFTWARE

	Package	Version	Filename
Word Processor	MS Word	2018	300-000000-XXX-SADTtoVLBI_MID_ICD.docx
Block diagrams			
Other			

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington, Macclesfield Cheshire SK11 9DL Registered in England & Wales Company Number: 07881918
Website	www.skatelescope.org

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TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF TABLES

LIST OF FIGURES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF ABBREVIATIONS

AD	Applicable Document
CI	Configuration Item
CSP	Central Science Processor
DDBH	Digital Data Back Haul
ESD	Electrostatic Discharge
FEC	Forward Error Correction
GBASE	Gigabit/Second Baseband
GE	Gigabit Ethernet
ICD	Interface Control Document
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organisation for Standardisation
LC	Little Connector
MAC	Media Access Code
M&C	Monitor and Control
MPO	Multi-fibre Push-On
MTU	Maximum Transmit Unit
NSDN	Non-Science Data Network
OM4	Optical Multimode 4
OSI	Open Systems Interconnection model (ISO/IEC 7498-1)
PTP	Precision Time Protocol
QSFP	Quad Small Form factor Pluggable
RD	Reference Document
RFI	Radio Frequency Interference
Rev	Revision
SADT	Signal and Data Transport
SAT	Synchronisation and Timing
SDP	Science Data Processor
SFF	Small Form Factor
SFP	Small form-factor pluggable
SKA	Square Kilometre Array
SKA1	Phase 1 of the SKA
SKA1-Mid	Mid frequency array of dishes of SKA1
TBC	To be confirmed
TBD	To be decided
TM	Telescope Manager
UDP	User Datagram Protocol
VLBI	Very Long Baseline Interferometry

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1 INTRODUCTION

1.1 Purpose

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1.2 Scope

This ICD aggregates all of the identified inter-element interfaces between the Signal and Data Transport (SADT) Element and the Very Long Baseline Interferometry (VLBI) Element where the SADT Consortium has been identified as the Interface Lead.

1.3 Boundaries of responsibilities

The SKA Office is the Owner of the SADT Element interfaces, and acts as the authority of the system architecture. The point of contact of the Owner is SKA Office Element System Engineer - SADT.

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Point of contact:	SaDT/MID System Engineer
Role:	Interface Leading Party
Responsibilities:	Drive the definition of the ICD
	Submit the ICD for review and approval

Party:	VLBI Consortium
Point of contact:	SKA VLBI Scientist
Role:	Interface Following Party
Responsibilities:	Assist with the definition of the ICD
	Review the ICD
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- SADT.NSDN – provision for Monitor and Control, and NTP services for VLBI.

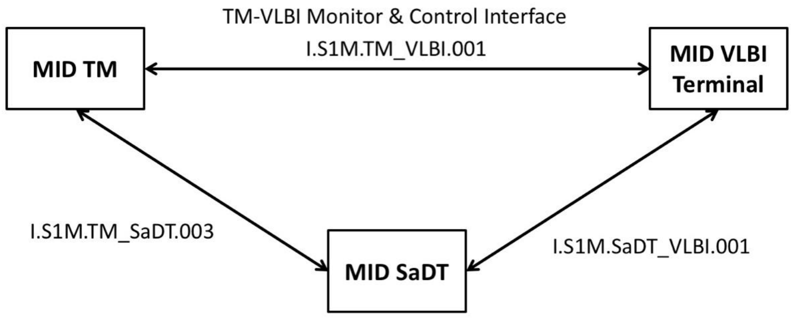

Figure 1. SADT-VLBI MID ICD Topology

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Unique identifiers are prescribed for each of the interfaces pertinent to the SADT-VLBI ICD; the methodology imposed shall permit the immediate identification of any given interface, and following the underlying logic:

I.S1T.xxxx_yyyy.nnn.ccc

Where periods are used as separators and digits are defined as follows:

I Defines the item as an interface
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T Defines whether the item pertains to the Telescope (T), MID (M) or LOW (L)
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ccc Text describing the data

Notes:
† Subsequent numbering/lettering to be used as appropriate for progressive project phases.
‡ A list of suitable element acronyms are tabulated (Table 1):

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I.S1M.SADT_VLBI.001	**NSDN** 342-000000	**VLBI Terminal** CIN (TBD.001)	Local Monitor and Control (LMC)

Table 1. SADT-VLBI Interface Identification

For example:

I.S1M.SADT_VLBI.001

Defines an interface (I) belonging to the SKA project (S), current under phase 1 (1), specifically to SKA1-Mid (M), where SADT element is lead (SADT) and interfaces with the VLBI Element (VLBI), and the specific interface is number 001.

In this ICD each interface will be identified, its constituents clearly and qualitatively described and fundamental requirements and specifications shall be disclosed. And finally, be supplemented by the element's respective Product Name and Configuration Item (CI) number, in the following manner:

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- **CSP Correlator and Beamformer** – 311-000000

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Safety aspects of interfaces arise from application of the safety provisions of the SKA Project Safety Management Plan [AD1], such as the mandatory Safety Assessment. In addition to the products of the Safety programme, safety critical interfaces shall be highlighted in ICDs as in any other design or operations related documents.

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- I.S1M.SADT_VLBI.001

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S.R.6	Optical Modules (SFP+ (10GBASE-LR) (10GBASE-LR), QSFP28 & long-haul optics)	Modules must be carefully and correctly seated into switching and long haul equipment, as described in manufacturer's instructions.
S.R.7	Cabling	Cables/Fibres to Switch Ports must be dressed into cable holders, both horizontally and vertically.
S.R.8	Unused optical interfaces	Unused optical interfaces on switch/long haul equipment must be closed using rubber plugs, for safety and environmental ingress protection.
S.R.9	Safety Standards	Safety standards as per industry "good practice."

Table 2. Safety Requirements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

5 INTERFACE IMPLEMENTATION SPECIFICATION

5.1 I.S1M.SADT_VLBI.001

Specifications are identified in Table 3

Specification Title	Verification ID	Specification
Interface Demarcation (SADT Product)	VER-300-xxx-001	**SPC_Core_Router** (CIN 142-054000) **QSFP28_Pluggable_Modules** (CIN 146-047000) (Terminating with 1 "Electrical Ends")
Interface Demarcation (VLBI Product)	VER-300-xxx-002	**VLBI Terminal** (CIN TBD.001) (Terminating with 1 **QSFP28 Transceiver Sockets**)
Mechanical Specification		
Optical Connectors	VER-300-xxx-003	SADT: **QSFP28_Pluggable_Module** VLBI: **QSFP28 Transceiver Socket**
SADT Interface Item	VER-300-xxx-004	One (1) instances of **QSFP28_Pluggable_Modules**
VLBI Interface Item	VER-300-xxx-005	One (1) instances **QSFP28 Transceiver Sockets**
Cabling Client-side	VER-300-xxx-006	SADT Provides all cable routing and management
Interfacing Item Proximity	VER-300-xxx-007	Distance between **SPC_Core_Router** and **VLBI Terminal** shall not exceed 30m, and shall, if possible reside in adjacent racks in the Science Processing Centre/Facility.
Electrical, Electronic and Electro-optical Specification		
Pluggable Modules	VER-300-xxx-008	**QSFP28_Pluggable_Modules** shall meet 4x25G Electrical I/O CAUI-4 and IEEE 802.3-2015
Power Specification		
Power: **QSFP28_Pluggable_Modules**	VER-300-xxx-009	VLBI shall provide 2.5 Watts DC for each instance of **QSFP28_Pluggable_Module** with power and connections defined in MSA SFF-8679, QSFP28 4X Base Electrical Specification.
Data Transport/Exchange Specification		
Wire Data Rate Across Interface	VER-300-xxx-010	100 Gbit/sec maximum physical links capacity
Data Link and Framing (OSI L2)	VER-300-xxx-011	As per Ethernet IEEE 802.3-2015 (with Jumbo frames IP MTU 9000 bytes)
Client-Side Link Capacity	VER-300-xxx-012	100Gbit/sec (as per Ethernet IEEE 802.3-2015) for 100GBASE-SR4✝
Forward Error Correction (FEC)	VER-300-xxx-013	Mandatory, as defined in IEEE 802.3-2015
Data Traffic Profile	VER-300-xxx-014	Bidirectional data flow.
Client-Side Link Load	VER-300-xxx-015	<80% Occupancy (total capacity) for each 100Gbit/sec link **(TBC)** but may operate at 100% capacity for peak load periods.
Flow control	VER-300-xxx-016	Provided by SADT NSDN equipment
Data buffering	VER-300-xxx-017	Buffering will support multiple classes of traffic.
Transport latency	VER-300-xxx-018	SADT equipment provides minimum latency
Packet Loss	VER-300-xxx-019	SADT provides $<7x10^{-8}$ MAC layer, $<7x10^{-11}$ with FEC 10^{-12} equivalent MAC BER, 10^{-15} with FEC (IEEE 802.3ba) [RD12]
Packet Out-of-Order	VER-300-xxx-020	No packets out of order (SADT provides point to point links)
Traffic Shape	VER-300-xxx-021	Bursty
Nested Header	VER-300-xxx-022	Supported
Packet Structure (pluggable interface)	VER-300-xxx-023	Ethernet/IP/TCP/Application Header/Data and Ethernet/IP/UDP
IP Internet Layer (OSI Layer 3)	VER-300-xxx-024	IPv4 RFC 791, and support IPv6 RFC 2460
Transport Layer	VER-300-xxx-025	TCP, UDP and multicast are available
Ethernet Switching	VER-300-xxx-026	Provided by SaDT

Table 3. I.S1M.SADT_VLBI.001 Interface Implementation

✝ Different flows on four components making up QSFP28 electrical interface not acceptable.

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6 INTERFACE VERIFICATION

Verification actions are summarised in the following table:

VER-300-xxx-001		
VER-300-xxx-002		
VER-300-xxx-003		
VER-300-xxx-004		
VER-300-xxx-005		
VER-300-xxx-006		
VER-300-xxx-007		
VER-300-xxx-008		
VER-300-xxx-009		
VER-300-xxx-010		
VER-300-xxx-011		
VER-300-xxx-012		
VER-300-xxx-013		
VER-300-xxx-014		
VER-300-xxx-015		
VER-300-xxx-016		
VER-300-xxx-017		
VER-300-xxx-018		
VER-300-xxx-019		
VER-300-xxx-020		
VER-300-xxx-021		
VER-300-xxx-022		
VER-300-xxx-023		
VER-300-xxx-024		
VER-300-xxx-025		
VER-300-xxx-026		

Table 4. Verification actions (I.S1M.SADT_VLBI.001)

7 TBD ITEMS

TBDs are summarised in the table below (Table 5):

Item No.	Description	Owner	Required
TBD.001	VLBI Terminal CIN	SKAO	System CDR

Table 5. Summary of TBDs

7.1 Known issues and outstanding items

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8 INTERFACE REQUIREMENTS

SADT Req. ID	Requirement

Table 6. SADT Requirements I.S1M.SADT_VLBI.001

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ANNEX 2.6 MID Science Data Processor (SDP) to VLBI ICD

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INTERFACE CONTROL DOCUMENT
SDP TO VLBI (MID)

Document Number	300-000000-XXX
Document Type	ICD
Revision	C
Author	F. Graser
Date	2018-11-23
Document Classification	FOR PROJECT USE ONLY
Status	Draft

Name	Designation	Affiliation	Signature
Owned by:			
F. Graser	SDP System Engineer	SDP Consortium	
Released by:			
Approved by:			

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DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2018-11-08	-	First draft
B	2018-11-14		Added SDP Consortium comments
C	2018-11-23		Added VLBI Consortium comments

DOCUMENT SOFTWARE

	Package	Version	Filename
Word Processor	MS Word	2018	300-000000-XXX-SDPtoVLBI_MID_ICD.docx
Block diagrams			
Other			

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington, Macclesfield Cheshire SK11 9DL Registered in England & Wales Company Number: 07881918
Website	www.skatelescope.org

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF TABLES

LIST OF FIGURES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF ABBREVIATIONS

AD	Applicable Document
CI	Configuration Item
CSP	Central Science Processor
DDBH	Digital Data Back Haul
ESD	Electrostatic Discharge
FEC	Forward Error Correction
GBASE	Gigabit/Second Baseband
GE	Gigabit Ethernet
ICD	Interface Control Document
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organisation for Standardisation
LC	Little Connector
MAC	Media Access Code
M&C	Monitor and Control
MPO	Multi-fibre Push-On
MTU	Maximum Transmit Unit
NSDN	Non-Science Data Network
OM4	Optical Multimode 4
OSI	Open Systems Interconnection model (ISO/IEC 7498-1)
PTP	Precision Time Protocol
QSFP	Quad Small Form factor Pluggable
RD	Reference Document
RFI	Radio Frequency Interference
Rev	Revision
SADT	Signal and Data Transport
SAT	Synchronisation and Timing
SDP	Science Data Processor
SFF	Small Form Factor
SFP	Small form-factor pluggable
SKA	Square Kilometre Array
SKA1	Phase 1 of the SKA
SKA1-Mid	Mid frequency array of dishes of SKA1
TBC	To be confirmed
TBD	To be decided
TM	Telescope Manager
UDP	User Datagram Protocol
VLBI	Very Long Baseline Interferometry

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

1 INTRODUCTION

1.1 Purpose

This Interface Control Document (ICD) defines the exchanges for each of the SDP Consortium led interfaces identified between the SDP Element and the VLBI Element for the SKA1-MID Telescope*. The VLBI Element is comprised by the VLBI Terminal described in [RD2].

*Note: the SKA1-LOW Telescope does not have an interface with SDP.

1.2 Scope

This ICD aggregates all of the identified inter-element interfaces between the Science Data Processor (SDP) Element and the Very Long Baseline Interferometry (VLBI) Element where the SDP Consortium has been identified as the Interface Lead.

1.3 Boundaries of responsibilities

The SKA Office is the Owner of the SDP Element interfaces, and acts as the authority of the system architecture. The point of contact of the Owner is SKA Office Element System Engineer - SDP.

The roles and responsibilities of the element consortia for the SDP led interfaces are as follows:

Party:	SDP Consortium
Point of contact:	SDP Consortium System Engineer
Role:	Interface Leading Party
Responsibilities:	Drive the definition of the ICD
	Submit the ICD for review and approval

Party:	SKAO SDP System Engineer/ VLBI Consortium
Point of contact:	MID System Engineer/ SKA VLBI Scientist
Role:	Interface Following Party
Responsibilities:	Assist with the definition of the ICD
	Review the ICD
	Approve the ICD

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2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

[AD1] SKA-TEL-SKO-0000008, "SKA Phase 1 Systems Requirements Specification"

[AD2] SKA-TEL-SKO-0000740, Rev 01, "SKA Project Safety Management Plan"

2.2 Reference documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD1] 300-000000-023 "SADT to CSP Interface Control Document"

[RD2] SKA-TEL-SKO-0000116, "SKA1 External VLBI Interface Control Document"

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3 INTERFACE DEFINITON

This Interface Control Document (ICD) describes the interfaces between SDP and VLBI Element that are allocated within the SKA1-MID Telescope. The VLBI Element [RD2] interfaces to one (1) SDP sub-elements:

- SDP.XXX (TBD.001) – provision for transport of science data to VLBI.

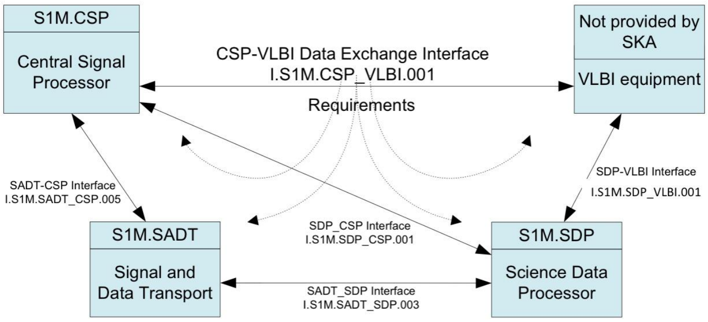

Figure 1. SDP-VLBI MID ICD Topology

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3.1 Interface Identification

Unique identifiers are prescribed for each of the interfaces pertinent to the SDP-VLBI ICD; the methodology imposed shall permit the immediate identification of any given interface, and following the underlying logic:

I.S1T.xxxx_yyyy.nnn.ccc

Where periods are used as separators and digits are defined as follows:

I	Defines the item as an interface
S	Defines that the item pertains to the SKA Project
1	Defines the item as being current at Phase 1†
T	Defines whether the item pertains to the Telescope (T), MID (M) or LOW (L)
xxxx	Defines the interfacing element 1 (lead)‡
yyyy	Defines interfacing element 2 (non-lead)‡
nnn	A unique number string between 001 and 999
ccc	Text describing the data

Notes:
† Subsequent numbering/lettering to be used as appropriate for progressive project phases.
‡ A list of suitable element acronyms are tabulated (Table 1):

Interface No.	SDP Product ID	VLBI Product ID	Interface Description
I.S1M.SDP_VLBI.001	**Data Processor** 336-000000	**VLBI Terminal** CIN (TBD.002)	VLBI Science Data (VLBI)

Table 1. SDP-VLBI Interface Identification

For example:

I.S1M.SDP_VLBI.001

Defines an interface (I) belonging to the SKA project (S), current under phase 1 (1), specifically to SKA1-Mid (M), where SDP element is lead (SDP) and interfaces with the VLBI Element (VLBI), and the specific interface is number 001.

In this ICD each interface will be identified, its constituents clearly and qualitatively described and fundamental requirements and specifications shall be disclosed. And finally, be supplemented by the element's respective Product Name and Configuration Item (CI) number, in the following manner:

- **Signal and Data Transport** – CI 305-000000
- **Data Processor** – CI 336-000000

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3.1.1 I.S1M.SDP_VLBI.001

Interface is between the **SDP** and **VLBI Element**, and facilitates data exchange relating to “VLBI” science data which has been processed by the Central Signal Processor (CSP).

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4 SAFETY ASPECTS

Safety aspects of interfaces arise from application of the safety provisions of the SKA Project Safety Management Plan [AD1], such as the mandatory Safety Assessment. In addition to the products of the Safety programme, safety critical interfaces shall be highlighted in ICDs as in any other design or operations related documents.

The optical components of the 10GE and 100GE links will use Laser Class 1 (or 1M) devices as described in IEC60825-1. Suitable labels warning about exposure will be attached. Optical modules such as SFP+ (10GBASE-LR) (10GBASE-LR), QSFP28 and long-haul optics are ESD class 2 and normal handling precautions should be observed to prevent damage from electrical discharges. The following table (Table 2) applies to interface:

- I.S1M.SDP_VLBI.001

No.	Title	Requirement
S.R.1	Optical components	Laser Class 1
S.R.2	Laser safety	Labels must be attached
S.R.3	SFP+	ESD class 2 (Line side is manufacturer specific)
S.R.4	QSFP28 modules	ESD class 2 (Line side is manufacturer specific)
S.R.5	ESD protection	Handling precautions as per manufacturer recommendations
S.R.6	Optical Modules (SFP+ (10GBASE-LR) (10GBASE-LR), QSFP28 & long-haul optics)	Modules must be carefully and correctly seated into switching and long haul equipment, as described in manufacturer's instructions.
S.R.7	Cabling	Cables/Fibres to Switch Ports must be dressed into cable holders, both horizontally and vertically.
S.R.8	Unused optical interfaces	Unused optical interfaces on switch/long haul equipment must be closed using rubber plugs, for safety and environmental ingress protection.
S.R.9	Safety Standards	Safety standards as per industry "good practice."

Table 2. Safety Requirements

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5 INTERFACE IMPLEMENTATION SPECIFICATION

5.1 I.S1M.SDP_VLBI.001

Specifications are identified in Table 3

Specification Title	Verification ID	Specification
Service Description	N/A	**VLBI Science Data** (**VLBI**)
Interface Demarcation (SDP Product)	VER-300-xxx-001	**Data Processor** (CIN 336-000000) (Terminating with 4 **QSFP28 Transceiver Sockets**)
Interface Demarcation (VLBI Product)	VER-300-xxx-002	**VLBI Terminal** (CIN TBD.002) **QSFP28_Pluggable_Modules** (CIN 346-047000) (Terminating with 4 “Electrical Ends”)
Mechanical Specification		
Optical Connectors	VER-300-xxx-003	SDP: **QSFP28 Transceiver Socket** VLBI: **QSFP28_Pluggable_Module**
SDP Interface Item	VER-300-xxx-004	Four (4) instances of **QSFP28 Transceiver Sockets**
VLBI Interface Item	VER-300-xxx-005	Four (4) instances **QSFP28_Pluggable_Modules**
Cabling Client-side	VER-300-xxx-006	SADT Provides all cable routing and management
Interfacing Item Proximity	VER-300-xxx-007	The **Data Processor** and **VLBI Terminal** shall not exceed 30m, and shall, if possible reside in adjacent racks in the Science Processing Centre/Facility.
Electrical, Electronic and Electro-optical Specification		
Pluggable Modules	VER-300-xxx-008	**QSFP28_Pluggable_Modules** shall meet 4x25G Electrical I/O CAUI-4 and IEEE 802.3-2015
Power Specification		
Power: **QSFP28_Pluggable_Modules**	VER-300-xxx-009	VLBI shall provide 2.5 Watts DC for each instance of **QSFP28_Pluggable_Module** with power and connections defined in MSA SFF-8679, QSFP28 4X Base Electrical Specification.
Data Transport/Exchange Specification		
Wire Data Rate Across Interface	VER-300-xxx-010	400 Gbit/sec maximum physical links capacity
Data Link and Framing (OSI L2)	VER-300-xxx-011	As per Ethernet IEEE 802.3-2015 (with Jumbo frames IP MTU 9000 bytes)
Client-Side Link Capacity	VER-300-xxx-012	100Gbit/sec (as per Ethernet IEEE 802.3-2015) for 100GBASE-SR4
Forward Error Correction (FEC)	VER-300-xxx-013	Mandatory, as defined in IEEE 802.3-2015
Data Traffic Profile	VER-300-xxx-014	Continuous unidirectional data flow (CSP to VLBI via SDP) Comprising UDP traffic
Client-Side Link Load	VER-300-xxx-015	<80% Occupancy (total capacity) for each 100Gbit/sec link (**TBC**) but may operate at 100% capacity for peak load periods.
Flow control	VER-300-xxx-016	No flow control provided by SDP
Data buffering	VER-300-xxx-017	No data buffering provided by SDP
Transport latency	VER-300-xxx-018	SDP equipment provides minimum latency
Packet Loss	VER-300-xxx-019	SDP provides $<7x10^{-8}$ MAC layer, $<7x10^{-11}$ with FEC 10^{-12} equivalent MAC BER, 10^{-15} with FEC (IEEE 802.3ba) [RD12]
Packet Out-of-Order	VER-300-xxx-020	No packets out of order (SDP provides point to point links)
Nested Header	VER-300-xxx-021	Implemented for VLBI
Packet Structure (pluggable interface)	VER-300-xxx-022	Ethernet/IP/UDP/Application Header/Science Data
IP Internet Layer (OSI Layer 3)	VER-300-xxx-023	IPv4 RFC 791
Transport Layer	VER-300-xxx-024	UDP RFC 768, Multicast RFC 1112, RFC 4606 (group management), RFC5771 (admin scoped addresses)
Application Header	VER-300-xxx-025	No special action to be taken, VDIF protocol is an application protocol carried by UDP/IP/Ethernet
Payload	VER-300-xxx-026	No special action to be taken, VDIF protocol is an application protocol carried by UDP/IP/Ethernet
Physical Layer Monitoring (SDP)	VER-300-xxx-027	SDP Collect OSI Layer 1 and 2 statistics from Ethernet modules on the SDP-Side of the interface. Access via TM.
Physical Layer Monitoring (VLBI)	VER-300-xxx-028	VLBI Collect OSI Layer 1 and 2 statistics from Ethernet modules on the VLBI-Side of the interface. Access via TM.

Table 3. I.S1M.SDP_VLBI.001 Interface Implementation

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6 INTERFACE VERIFICATION

Verification actions are summarised in the following tables:

VER-300-xxx-001		
VER-300-xxx-002		
VER-300-xxx-003		
VER-300-xxx-004		
VER-300-xxx-005		
VER-300-xxx-006		
VER-300-xxx-007		
VER-300-xxx-008		
VER-300-xxx-009		
VER-300-xxx-010		
VER-300-xxx-011		
VER-300-xxx-012		
VER-300-xxx-013		
VER-300-xxx-014		
VER-300-xxx-015		
VER-300-xxx-016		
VER-300-xxx-017		
VER-300-xxx-018		
VER-300-xxx-019		
VER-300-xxx-020		
VER-300-xxx-021		
VER-300-xxx-022		
VER-300-xxx-023		
VER-300-xxx-024		
VER-300-xxx-025		
VER-300-xxx-026		
VER-300-xxx-027		
VER-300-xxx-028		

Table 4. Verification actions (I.S1M.SDP_VLBI.001)

7 TBD ITEMS

TBDs are summarised in the table below (Table 5):

Item No.	Description	Owner	Required
TBD.001	SDP.XXX sub-element that interfaces with the VLBI Element	SKAO	System CDR
TBD.002	VLBI Terminal CIN	SKAO	System CDR

Table 5. Summary of TBDs

7.1 Known issues and outstanding items

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

8 INTERFACE REQUIREMENTS

SADT Req. ID	Requirement

Table 6. SDP Requirements I.S1M.SDP_VLBI.001

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ANNEX 3: VLBI L1 System Level Requirements Review

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

SKA PHASE 1 VLBI L1 REQUIREMENTS

Document number	SKA-TEL-SKO-0000XX
Context	Operations Planning Group
Revision	B
Author	C. Garcia-Miro
Date	2018-11-27
Document Classification	UNRESTRICTED
Status	Released

Name	Designation	Affiliation	Signature	
Authored by:				
C. Garcia-Miro	VLBI Scientist	SKA Office		
			Date:	2018-11-27
Owned by:				
			Date:	
Approved by:				
		SKA Office		
			Date	
Released by:				
		SKA Office		

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

			Date	

DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2018-11-01	**ECP-140008:** Clarification of VLBI Capabilities and Requirements **ECP-160040:** Adding VLBI Capabilities to SKA1- Low **ECP-160043:** Subarray Requirements **ECP-170017:** CSP Mid.CBF Frequency Slice Approach	First draft
B	2018-11-27		Added Comments from VLBI Consortium (lead by JIVE)

DOCUMENT SOFTWARE

	Package	Version	Filename
Wordprocessor	MS Word	Word 2018	SKA-TEL-SKO-0000XXX VLBI L1 requirements
Block diagrams			
Other			

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington Macclesfield Cheshire SK11 9DL United Kingdom Registered in England & Wales Company Number: 07881918
Fax.	+44 (0)161 306 9600
Website	www.skatelescope.org

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF FIGURES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

LIST OF ABBREVIATIONS

AD	Applicable Document
CI	Configuration Item
CSP	Central Science Processor
DDBH	Digital Data Back Haul
ESD	Electrostatic Discharge
FEC	Forward Error Correction
GBASE	Gigabit/Second Baseband
GE	Gigabit Ethernet
ICD	Interface Control Document
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organisation for Standardisation
LC	Little Connector
MAC	Media Access Code
M&C	Monitor and Control
MPO	Multi-fibre Push-On
MTU	Maximum Transmit Unit
NSDN	Non-Science Data Network
OM4	Optical Multimode 4
OSI	Open Systems Interconnection model (ISO/IEC 7498-1)
PTP	Precision Time Protocol
QSFP	Quad Small Form factor Pluggable
RD	Reference Document
RFI	Radio Frequency Interference
Rev	Revision
SADT	Signal and Data Transport
SAT	Synchronisation and Timing
SDP	Science Data Processor
SFF	Small Form Factor
SFP	Small form-factor pluggable
SPC	Science Processing Centre
SKA	Square Kilometre Array
SKA1	Phase 1 of the SKA
SKA1-Mid	Mid frequency array of dishes of SKA1
TBC	To be confirmed
TBD	To be decided
TM	Telescope Manager
UDP	User Datagram Protocol
VLBI	Very Long Baseline Interferometry

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

1 Introduction

1.1 Purpose of Document

The changes proposed in this document should be considered to be included in the next revision of the SKA Level 1 Requirements.

A basic set of VLBI requirements is provided in the L1 Requirements Rev 11 but this set is not considered complete. Specifically:

- Implementation/refinement of requirements from VLBI ECP incomplete – ECP140008
- Review and definition of detailed/new VLBI requirements, including L1 – ECP140008, ECP160040
- Requirements need to be harmonized between SKA1-Mid and SKA1-Low, ECP160040
- VLBI related elements interface requirements need attention.
- SKA1 to VLBI external interface SKA-TEL-SKO-0000116

Present report is based on inputs from: VLBI Clarification document, CSP assumptions, CDR outcomes for CSP, SADT, TM, pre-CDR SDP.

1.2 Scope of the document

This document summarizes various proposed changes to Level 1 requirements related to the VLBI capability.

2 Applicable and Reference Documents

2.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

[AD1] SKA Phase 1 System (Level 1) Requirements Specification, SKA-TEL-SKO-0000008, Rev 11

[AD2] Interface Control Document SADT to CSP (MID), 300-000000-023, Rev 3

[AD3] Interface Control Document SADT to CSP (LOW), 100-000000-023, Rev 3

[AD4] Interface Control Document SDP to CSP (MID), 300-000000-002, Rev 3

[AD5] Interface Control Document SADT to SDP (MID), 300-000000-025, Rev 4

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2.2 Reference documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD1] SKA1_MID Telescope Interface Control Document CSP to VLBI, 300-000000-032, Rev 1

[RD2] SKA1_LOW Telescope Interface Control Document CSP to VLBI, 100-000000-032, Rev 1

[RD3] SKA1 Interface Control Document TM to VLBI, SKA-TEL-SKO-0000932, Rev 1

[RD4] SKA1_MID Telescope Interface Control Document SADT to VLBI, 300-000000-xxx, draft

[RD5] SKA1_LOW Telescope Interface Control Document SADT to VLBI, 100-000000-xxx, draft

[RD6] SKA1_MID Telescope Interface Control Document SDP to VLBI, 300-000000-xxx, draft

[RD7] SKA1 CSP Architectural Design Document, SKA-TEL-CSP-0000014, Rev 5

[RD8] SKA1 Operational Concept Document, SKA-TEL-SKO-0000307, Rev 3

[RD9] SKA1 External VLBI Interface Control Document, SKA-TEL-SKO-0000116, Rev 1

[RD10] SKA1 Scientific Use Cases, SKA-TEL-SKO-0000015, Rev 3

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3 Overview

A review of the justification, consistency and identification of gaps in the Level 1 VLBI related System requirements has been carried out, ensuring appropriate flow down into Level 2 and Level 3 requirements for the different SKA1 Elements. Special attention was required for the SKA1 LOW telescope as the VLBI capability was only recently introduced into its design.

The outcomes presented in this review are the result of consultation with the members of the VLBI science working group, discussions held with involved SKA Consortia during CDRs, and discussions held with the VLBI Consortium representatives (JIVE). Additionally, the assumptions raised by the different elements on VLBI L1 System level requirements are also informing this study, whenever pertinent.

As a result, 33 new VLBI requirements are proposed to be added and 40 of the original 66 requirements need amendment (Figures 1-5, highlighted in red). These requirements are subjected to approval by the SKAO Configuration Control Board (CCB) via the Engineering Change Proposal (ECP) process.

All SKA1 Elements are compliant with the new proposed requirements. There is only one requirement for beamforming, considered as useful, that is not included in the SKA1 design (direction-dependent corrections for beamforming).

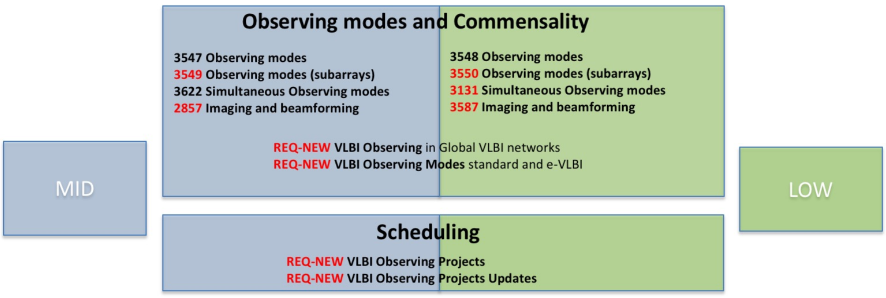

Figure 1. Observing modes and Commensality requirements (top). Scheduling requirements (bottom)

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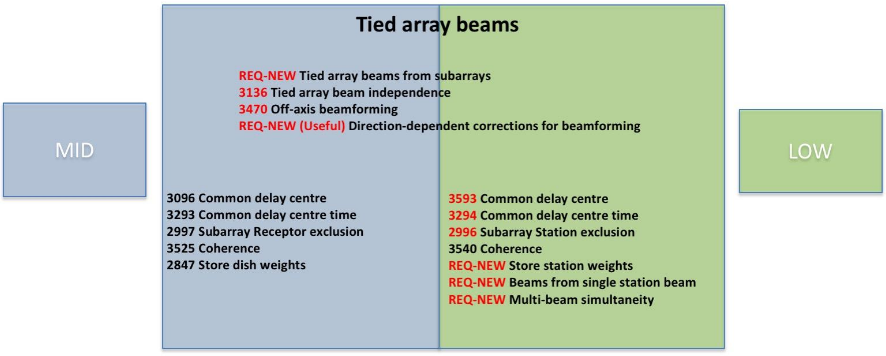

Figure 2. Tied array beams generic requirements.

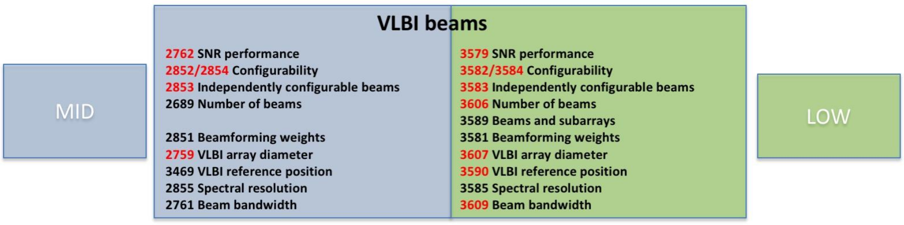

Figure 3. VLBI beams specific requirements.

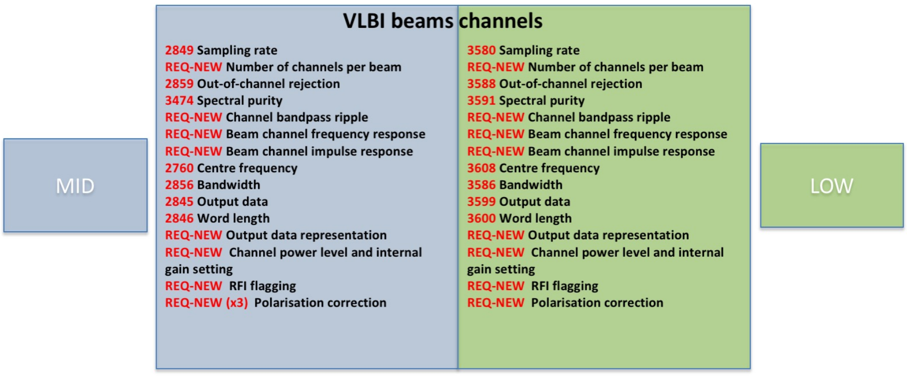

Figure 4. VLBI beam channels requirements.

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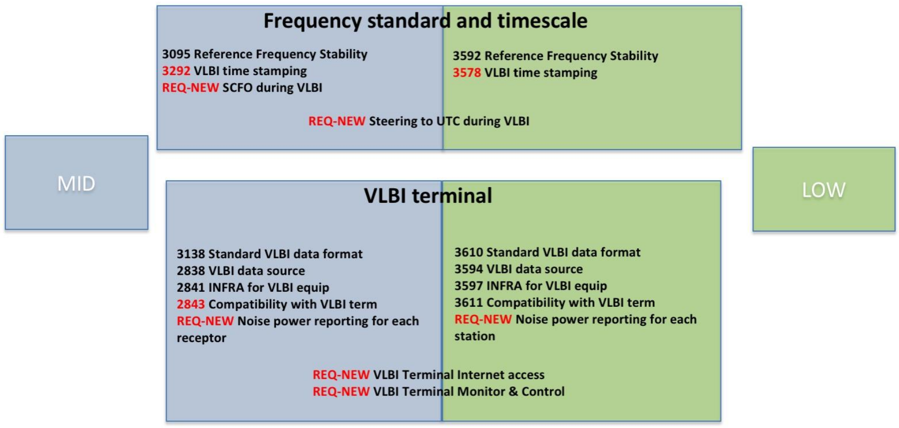

Figure 5. Frequency standard and timescale requirements (top). VLBI Terminal requirements (bottom).

4 Current L1 VLBI Requirements

This section of the document details the current set of requirements related to VLBI capability within the Level 1 requirements and provides a set of proposed updated requirements for consideration within the context of the ECP submission. Proposed amendments are highlighted in red.

It should be noted that the issued requirements [AD1] take precedence and that the current requirements listed below are for convenience only. Any potential review by a CRB should consider them in terms of completeness and correctness.

This section is structured in three subsections: SKA1-COMMON VLBI requirements, SKA1-LOW VLBI specific requirements and SKA1-MID VLBI specific requirements. Each subsection is divided in topics, e.g. requirements for tied-array beams, VLBI beams, VLBI beam-channels, etc.

4.1 SKA1-COMMON Requirements

4.1.1 Observing modes and Commensality

Requirements are specified in each telescope SKA1-MID and SKA1-LOW subsection.

4.1.2 Scheduling

Requirements are specified in each telescope SKA1-MID and SKA1-LOW subsection.

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4.1.3 Tied-array beams

SKA1-SYS_REQ-3136	**Tied array beam independence** The SKA1_Mid and SKA1_Low, when commanded, shall form tied-array beams that can be configured and operated independently of each other.
Allocation	TM, CSP
Proposed Description	**Tied array beam independence** The SKA1_Mid and SKA1_Low, when commanded, shall form tied-array beams that can be configured and operated independently of each other, only in scan boundaries.
Rationale	No compliance for tied array beams formed from the same subarray as scan definition is common for the different processing modes performed simultaneously in the subarray (only one host scheduling block can be executed in the subarray) [RD7][RD8].
Risk	Medium

SKA1-SYS_REQ-3470	**Off-axis beamforming** SKA1_Mid and SKA1_Low, when commanded, shall form tied-array beams for pulsar search and pulsar timing (and VLBI, for SKA1_Mid), whose half-power contour fits entirely within the half-power primary beam width of the largest receptors in use, calculated at the highest frequency within the frequency range covered by the tied-array beam in question.
Allocation	CSP
Proposed Description	**Off-axis beamforming** SKA1_Mid and SKA1_Low, when commanded, shall form tied-array beams for pulsar search,~~ and~~ pulsar timing, ~~(~~and VLBI, ~~for SKA1_Mid),~~ whose half-power contour fits entirely within the half-power primary beam width of the largest receptors in use, calculated at the highest frequency within the frequency range covered by the tied-array beam in question.
Proposed Allocation	CSP, TM
Rationale	Adding VLBI to SKA1-LOW (ECP-160040) and allocation to TM (when commanded).
Risk	Medium

4.1.4 VLBI beams

Requirements are specified in each telescope SKA1-MID and SKA1-LOW subsection.

4.1.5 VLBI beam-channels

Requirements are specified in each telescope SKA1-MID and SKA1-LOW subsection.

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4.1.6 Frequency standard and timescale

Requirements are specified in each telescope SKA1-MID and SKA1-LOW subsection.

4.1.7 VLBI Terminal

Requirements are specified in each telescope SKA1-MID and SKA1-LOW subsection.

4.2 SKA1-LOW Requirements

4.2.1 Observing modes and Commensality

SKA1-SYS_REQ-3548	**Observing modes (SKA1_Low telescope)** The SKA1_Low telescope, when commanded, shall operate simultaneously with any combination of the following observing modes: ● Imaging ● Pulsar Search ● Pulsar Timing ● Dynamic Spectrum ● Transient Search ● VLBI
Allocation	CSP, SDP, TM

SKA1-SYS_REQ-3550	**SKA1_Low observing modes (subarrays)** SKA1_Low subarrays, when commanded, shall operate simultaneously with any combination of the following observing modes: ● Imaging ● Pulsar Search ● Pulsar Timing ● Dynamic Spectrum ● Transient Search
Allocation	CSP, SDP, TM
Proposed Description	**SKA1_Low observing modes (subarrays)** SKA1_Low subarrays, when commanded, shall operate simultaneously with any combination of the following observing modes: ● Imaging ● Pulsar Search ● Pulsar Timing ● Dynamic Spectrum ● Transient Search ● VLBI

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Rationale	VLBI missing in this requirement, at least VLBI needs to be concurrent with Imaging in the same subarray for beamforming. Commensal observing VLBI and normal Imaging is asked in VLBI science cases (e.g. 3.30 Stellar Cluster Deep Field, 3.49 Parallax measurement of Southern Hemisphere pulsar, etc. [RD10]). Currently there are no SKA1-LOW specific science cases but the VLBI SWG group is preparing them. SKA1-LOW can support full commensality within the same sub-array [RD7].
Risk	Medium

SKA1-SYS_REQ-3131	**SKA1_Low Simultaneous Observing Modes** SKA1_Low, when commanded shall provide processing within a subarray for one of: 1. Simultaneous imaging and non-imaging observing. 2. Simultaneous imaging and VLBI observing.
Allocation	TM, CSP, SDP
Proposed Allocation	TM, CSP, ~~SDP~~
Proposed Description	**SKA1_Low Simultaneous Observing Modes** SKA1_Low, when commanded shall provide processing within a subarray for simultaneous imaging, non-imaging and VLBI observing.
Rationale	The action of the requirement "processing" is performed by CSP and controlled by TM, no allocation needed for SDP. Equivalent Mid requirement not allocated to SDP. SKA1-LOW can support full commensality within the same sub-array [RD7].
Risk	Low

SKA1-SYS_REQ-3587	**SKA1_Low VLBI imaging and beamforming** SKA1_Low, when commanded, shall simultaneously generate both VLBI beams and SKA1_Low imaging data for all polarization products and all baselines (including autocorrelations) with a spectral resolution no worse than 1 MHz, covering at least the larger of 100 MHz TBC or the frequency range(s) covered by the VLBI beam(s) within the associated subarray.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, SADT, SDP
Proposed Description	**SKA1_Low VLBI imaging and beamforming** SKA1_Low, when commanded, shall simultaneously generate both VLBI beams and SKA1_Low images for all polarization products and all baselines (including autocorrelations) with a spectral resolution of 5kHz +-20% for at least the frequency range covered by the LFAA beam that contain the VLBI beam within the associated subarray.
Rationale	Simultaneous VLBI beams and imaging including SDP imaging products (maps). Imaging resolution updated. SKA1-CSP_ASS-312
Risk	Low

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4.2.2 Scheduling

Requirements are specified in the SKA1-COMMON subsection.

4.2.3 Tied-array beams

SKA1-SYS_REQ-3593	**SKA1_Low Common Delay Centre** The SKA1_Low shall determine each effective sub-array position in absolute terms (i.e. relative to the centre of the earth, not each other) to an accuracy of better than 1 cm. At each of these geographical reference positions the time will be traceable to the SKA timescale with an accuracy as specified by the Time stamping requirement.
Allocation	SDP, TM

SKA1-SYS_REQ-3294	**SKA1_Low common delay centre time** Each SKA1_Low subarray shall have a common delay centre at or near its centre with a time accurate to the SKA timescale and a precision of better than 2ns (1σ) over periods of one observation and at least 10 years.
Allocation	CSP, SADT, TM

SKA1-SYS_REQ-2996	**SKA1_Low subarray tied-array beam station exclusion** The SKA1_Low shall assign dynamic weights to stations within a subarray contributing to tied-array beams including the ability to exclude individual stations.
Allocation	CSP, TM
Proposed Allocation	CSP, SDP, TM
Rationale	Analogous Mid requirement allocated to SDP.
Risk	Low

SKA1-SYS_REQ-3540	**Coherence of SKA1_Low tied-array beams** When commanded, SKA1_Low shall form pulsar search, pulsar timing, and VLBI tied-array beams that each have a coherence within 5% of that allowed by the current atmospheric conditions.
Allocation	SDP, TM, CSP

4.2.4 VLBI beams

SKA1-SYS_REQ-3579	**SKA1_Low S/N Performance** The SKA1_Low, when forming VLBI beams, shall have a signal-to-noise performance better than 90% of that achievable by an ideal signal chain, given the same inputs, instrumental calibration and excluding RFI.
Allocation	CSP, SADT
Proposed Allocation	CSP, ~~SADT~~, LFAA

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Proposed Description	**SKA1_Low VLBI S/N Performance** The SKA1_Low, when forming VLBI beams, shall have a signal-to-noise performance better than 90% of that achievable by an ideal analogue beamformer, given the same digitized inputs, instrumental calibration and excluding RFI.
Rationale	Change title to refer to the VLBI capability, as for Mid analogue requirement REQ-2762. Change text, as for similar PSS and PST requirements (REQ-2896, REQ-2930). Change allocation to CSP and LFAA, as this requirement just deals with beamforming DSP budget. Discussed and agreed with SADT that it should not be allocated to SADT.
Risk	Low

SKA1-SYS_REQ-3582	**SKA1_Low Configurability** SKA1_Low, when commanded, shall change the pointing, centre frequency, and bandwidth of each VLBI tied-array beam independently, on scan boundaries.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Low VLBI Configurability** SKA1_Low, when commanded, shall change the pointing, centre frequency, and bandwidth of each VLBI tied-array beam independently, on scan boundaries.
Rationale	Change title to refer to the VLBI capability, as for Mid analogue requirement REQ-2852. Discussed and agreed with SADT that should not be allocated to SADT.
Risk	Low

SKA1-SYS_REQ-3584	**SKA1_Low VLBI configurability** SKA1_Low shall, when commanded, reconfigure the centre frequency, frequency band, and bandwidth for each VLBI beam, in less than 30 seconds.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Rationale	Discussed and agreed with SADT that should not be allocated to SADT.
Risk	Low

SKA1-SYS_REQ-3583	**SKA1_Low Independently configurable beams** SKA1_Low, when commanded, shall provide, through configuration, 1, 2, 3, or 4 separate VLBI specific beams, each with independently selectable centre frequency, bandwidth, frequency resolution and pointing.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Low VLBI Independently configurable beams** SKA1_Low, when commanded, shall provide, through configuration, 1, 2, 3, or 4 separate VLBI specific beams, each with independently selectable centre frequency, bandwidth, frequency resolution and pointing.
Rationale	Added VLBI to title as for Mid requirement Discussed and agreed with SADT that should not be allocated to SADT.
Risk	Low

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SKA1-SYS_REQ-3606	**SKA1_Low VLBI number of beams** The SKA1_Low correlator shall have the capability of producing 4 dual polarisation tied-array VLBI beams TBC for one SKA1_Low sub-array.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Low VLBI number of beams** SKA1_Low, when commanded, shall produce a total of up to four VLBI beams, spread across one or more subarrays.
Rationale	Removed mention to correlator, removed TBC. Discussed and agreed with SADT that should not be allocated to SADT. Aligned with Mid requirement. SKA1-CSP_ASS-417
Risk	Low

SKA1-SYS_REQ-3589	**SKA1_Low VLBI beams and subarrays** SKA1_Low shall be able to allocate individual VLBI beams to different subarrays.
Allocation	CSP, TM

SKA1-SYS_REQ-3581	**SKA1_Low Beamforming weights** SKA1_Low, when commanded, shall weight the Field Station beams, which are inputs into the VLBI tied-array sums, based on relative sensitivity and coherence losses.
Allocation	CSP, TM, SDP

SKA1-SYS_REQ-3607	**SKA1_Low VLBI array diameter** The SKA1_Low correlator shall be capable of forming 4 beams TBC across all stations within the VLBI sub-array to a distance of up to 100,000 TBC metres from the sub-array centre.
Allocation	CSP
Proposed Allocation	CSP, TM
Proposed Description	**SKA1_Low VLBI array diameter** Each SKA1_Low subarray, when configured for VLBI, shall form VLBI beams using all stations within the sub-array that are separated by at most 20 km.
Rationale	Allocation to TM as analogous Mid requirement. Beamforming as PST REQ-2922.

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	SKA1-CSP_ASS-418
Risk	Low

SKA1-SYS_REQ-3590	**SKA1_Low VLBI reference position** The SKA1_Low VLBI array phase centre shall be within 100km (TBC) of one of the SKA1_Low stations.
Allocation	CSP, TM, SDP
Proposed Description	**SKA1_Low VLBI reference position** The SKA1_Low VLBI array phase centre shall be within 2km of the centre of the circle that enclose SKA1_Low stations in the VLBI subarray.
Rationale	Limit VLBI subarray to 20Km as PST beamforming, and reference position to 2Km SKA1-CSP_ASS-416
Risk	Low

SKA1-SYS_REQ-3585	**SKA1_Low VLBI spectral resolution** SKA1_Low shall, when commanded, generate VLBI beams with a spectral resolution different from the spectral resolution used for imaging within the same subarray.
Allocation	CSP, TM

SKA1-SYS_REQ-3609	**SKA1_Low VLBI beam bandwidth** The SKA1_Low VLBI beams shall have a contiguous processing bandwidth up to the full bandwidth of the SKA1_Low array.
Allocation	CSP
Proposed Allocation	CSP, TM, SADT
Proposed Description	**SKA1_Low VLBI beam bandwidth** The SKA1_Low VLBI beams shall have a contiguous processing bandwidth up to 256 MHz, tunable within the full bandwidth of the SKA1_Low array.
Rationale	Allocation to SADT and TM as analogous Mid requirement. Low provides a maximum of 4x64 MHz, up to 256 MHz bandwidth [RD2], [RD7].
Risk	Low

4.2.5 VLBI beam-channels

SKA1-SYS_REQ-3580	**SKA1_Low VLBI beams sampling rate** SKA1_Low, when forming VLBI beams, shall output them with a sampling rate selectable between Nyquist and at least a factor of two oversampling for the selected bandwidth.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Low VLBI beams sampling rate (Useful)** SKA1_Low, when forming VLBI beams, shall output them with a sampling rate selectable between Nyquist and at least a factor of two oversampling for the

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	selected bandwidth.
Rationale	Discussed and agreed with SADT that should not be allocated to SADT. Modern software correlators do not require oversampling, classified as useful.
Risk	Low

SKA1-SYS_REQ-3588	**SKA1_Low VLBI out-of-channel rejection** SKA1_Low, when commanded, shall generate VLBI beams with a transition band that is monotonically decreasing from -3dB at the channel edge, to -60dB at a frequency offset from the centre frequency by the channel bandwidth.
Allocation	CSP, TM
Proposed Description	**SKA1_Low VLBI out-of-channel rejection** SKA1_Low, when commanded, shall generate VLBI beams channels with a transition band that is monotonically decreasing from -3dB at the channel edge, to -60dB at a frequency offset from the centre frequency by the beam channel bandwidth.
Rationale	Clarified text referring to beam channels.
Risk	Low

SKA1-SYS_REQ-3591	**SKA1_Low VLBI: spectral purity** Spectral distortion, after calibration, for SKA1_Low VLBI shall be below: • -30dB in amplitude • 0.01 radians in phase
Allocation	CSP
Proposed Allocation	CSP, LFAA
Proposed Description	**SKA1_Low VLBI: spectral purity** Spectral distortion of VLBI beams, after calibration, ~~for SKA1_Low VLBI~~ compared to an ideal analogue beamformer provided with the same inputs, shall be below: • -30dB in amplitude

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	• 0.03 radians in phase
Rationale	-30dB is 3% error in amplitude, a quadrature amplitude error of 3% introduces a phase error of 0.03 radians. Changed text as for similar PSS and PST requirements. Allocated to LFAA as it contributes to the DSP budget. SKA1-CSP_ASS-313
Risk	Medium

SKA1-SYS_REQ-3608	**SKA1_Low VLBI beam centre frequency** The SKA1_Low VLBI beams shall have a centre frequency selectable anywhere within the SKA1_Low observing band.
Allocation	CSP
Proposed Allocation	CSP, TM
Proposed Description	**SKA1_Low VLBI beam centre frequency** The SKA1_Low VLBI beam-channels within a beam shall have a contiguous centre frequency selectable anywhere within the SKA1_Low observing band, tunable with 0.01MHz resolution.
Rationale	Allocation to TM (tunable). Better description of Low capabilities [RD2] [RD7].
Risk	Low

SKA1-SYS_REQ-3586	**SKA1_Low VLBI channel width** SKA1_Low shall be able to generate VLBI beam data with a selectable channel width of: 256, 128, 64, 32, 16, 8, 4, 2, or 1 MHz TBC.
Allocation	CSP, TM
Proposed Description	**SKA1_Low VLBI beam channel sampled bandwidth.** SKA1_Low shall be able to generate VLBI beam data with a selectable channel width of: ~~256, 128,~~ 64, 32, 16, 8, 4, 2, or 1 MHz ~~TBC~~, such that the beam-channel lies entirely within the SKA1_Low band.
Rationale	Modified according to Low capabilities [RD2], [RD7]. SKA1-CSP_ASS-257
Risk	Low

SKA1-SYS_REQ-3599	**SKA1_Low VLBI beam output data** SKA1_Low shall be able to produce VLBI beam output data with either dual or single polarization.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Low VLBI beam output data** SKA1_Low shall be able to produce VLBI beam channel output data with either dual or single polarization.
Rationale	Discussed and agreed with SADT that should not be allocated to SADT. Clarified text referring to beam channels.
Risk	Low

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SKA1-SYS_REQ-3600	**SKA1_Low Word length of VLBI beam output data** SKA1_Low shall be able to output VLBI beam data with configurable word formats, the allowed values being 2, 4, and 8-bit integer TBC.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Low Word length of VLBI beam output data** SKA1_Low shall be able to output VLBI beam channel data with configurable word formats, the allowed values being 2, 4, and 8-bit integer ~~TBC~~.
Rationale	Discussed and agreed with SADT that should not be allocated to SADT. Clarified text referring to beam channels. SKA1-CSP_ASS-420
Risk	Low

4.2.6 Frequency standard and timescale

SKA1-SYS_REQ-3092	**SKA1_Low VLBI Reference Frequency Stability** The SKA1_Low timescales shall have a frequency stability, expressed as Allan Deviation, of at least: **AVERAGING TIME [S]** — **STABILITY** 1 — $2.0\ 10^{-13}$ 10 — $5.0\ 10^{-14}$ 100 — $1.3\ 10^{-14}$ 1000 — $3.2\ 10^{-15}$ floor up to 10^5 — $3.0\ 10^{-15}$
Allocation	SADT
Rationale	For Low frequencies this requirement can be relaxed, Rubidium stability is enough (as for LOFAR).
Risk	Low

SKA1-SYS_REQ-3578	**SKA1_Mid VLBI time stamping** Each SKA1_Mid VLBI data sample shall be directly traceable to the time at the common delay centre of the SKA1_Mid telescope, with an accuracy of better than 2 nanoseconds.
Allocation	CSP, SADT, DSH
Proposed Description	**SKA1_Mid VLBI time stamping** Each SKA1_Mid VLBI data sample shall be directly traceable to the time at the common delay centre of the SKA1_Mid telescope, with an accuracy of better than 0.05 microseconds.
Rationale	Discussed with VLBI SWG: constant offset of no more than 100 microseconds with accuracy better than 0.05 microseconds (as per Mark5B experience).
Risk	Low

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4.2.7 VLBI Terminal

SKA1-SYS_REQ-3610	**SKA1_Low Standard VLBI formats** SKA1_Low VLBI data shall conform to the SKA-VLBI ICD (to be written).
Allocation	TM
Proposed Allocation	TM, CSP
Proposed Description	**SKA1_Low Standard VLBI formats** SKA1_Low VLBI data shall conform to the SKA-VLBI ICD ~~(to be written)~~.
Rationale	Allocation to CSP as they produce the VDIF packets. SKA-VLBI ICD [RD9].
Risk	Low

SKA1-SYS_REQ-3594	**SKA1_Low VLBI data sources** The SKA1_Low telescope shall be a data source for VLBI data acquisition system. The interface between the SKA1_Low telescope and the external VLBI data acquisition system will be compliant with the ICD SKA-TEL-SKO-0000116.
Allocation	INFRA, CSP, TM, SADT

SKA1-SYS_REQ-3597	**SKA1_Low Infrastructure for VLBI equipment:** The following infrastructure shall be provided to allow eventual outfitting of SKA1_Low with VLBI equipment: 1. Adequate access for the potential fitment of VLBI equipment 2. Equipment space 3. Power 4. Cooling 5. Cable trays
Allocation	INFRA

SKA1-SYS_REQ-3611	**SKA1_Low Compatibility with existing VLBI terminal** SKA1_Low shall be able to output VLBI beam data with each individual stream limited to the entire SKA1_Low band to ensure compatibility with existing VLBI terminal capability.
Allocation	CSP, SADT
Rationale	Existing VLBI terminal capability can accept > 512 MHz signal bandwidth, not an issue for Low.
Risk	Low

4.3 SKA1-MID Requirements

4.3.1 Observing modes and Commensality

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SKA1-SYS_REQ-3547	**Observing modes (SKA1_Mid telescope)** The SKA1_Mid telescope, when commanded, shall operate simultaneously with any combination of the following observing modes: ● Imaging ● Pulsar Search ● Pulsar Timing ● Dynamic Spectrum ● Transient Search ● VLBI
Allocation	CSP, SDP, TM

SKA1-SYS_REQ-3549	**SKA1_Mid observing modes (subarrays)** SKA1_Mid subarrays, when commanded, shall operate simultaneously with any combination of observing modes within each of the following configurations: Configuration 1 ● Imaging ● Pulsar Search ● Pulsar Timing ● Dynamic Spectrum ● Transient Search Configuration 2 ● Imaging (in support of VLBI) ● Transient Search ● VLBI
Allocation	CSP, SDP, TM
Proposed Description	**SKA1_Mid observing modes (subarrays)** SKA1_Mid subarrays, when commanded, shall operate simultaneously with any combination of the following observing modes: ● Imaging (normal and in support of VLBI) ● Pulsar Search ● Pulsar Timing ● Dynamic Spectrum ● Transient Search ● VLBI
Rationale	Commensal observing VLBI and normal Imaging is asked in VLBI science cases within the same sub-array (e.g. 3.30 Stellar Cluster Deep Field, 3.49 Parallax measurement of Southern Hemisphere pulsar, etc. [RD10]) as well as simultaneous PSS (e.g. 3.52 Resolving ultra-relativistic outflows [RD10]). FSA architecture allows more flexibility within each subarray therefore, SKA1-MID can support full commensality within the same subarray with a bandwidth sacrifice. Difference between Configuration 1 and 2 may be removed to simplify Operations, with the caveat of bandwidth limitation due to limited resources.
Risk	Medium

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SKA1-SYS_REQ-3622	**SKA1_Mid Simultaneous Observing Modes** When commanded SKA1_Mid shall provide: 1. Fully simultaneous processing for imaging, non-imaging and VLBI observations within and across all Bands to the extent that processing and communication bandwidth resources are available and 2. Sufficient processing and communication resources to provide any one individually of: imaging, non-imaging and VLBI observations at full bandwidth beam product.
Allocation	TM, CSP

SKA1-SYS_REQ-2857	**SKA1_Mid VLBI: imaging and beamforming** SKA1_Mid, when commanded, shall simultaneously generate both VLBI beams and VLBI imaging data for the same subarray. VLBI imaging data shall include all polarization products and all baselines (including autocorrelations), with a spectral resolution no worse than 1 MHz, covering a bandwidth of at least 100 MHz, and spanning the full frequency range(s) covered by the VLBI beam(s) generated within the same subarray.
Allocation	CSP, TM, SADT, SDP
Proposed Description	**SKA1_Mid VLBI: imaging and beamforming** SKA1_Mid, when commanded, shall simultaneously generate both VLBI beams and SKA1_Mid images for the same subarray. Imaging products shall include all polarization products and all baselines (including autocorrelations), with a spectral resolution no worse than 1 MHz, covering a bandwidth of at least 100 MHz, and spanning the full frequency range(s) covered by the VLBI beam(s) generated within the same subarray.
Rationale	Simultaneous VLBI imaging for the same subarray including SDP imaging products (maps).
Risk	Medium

4.3.2 Scheduling

This topic requirements are specified in the SKA1-COMMON subsection.

4.3.3 Tied-array beams

SKA1-SYS_REQ-3096	**SKA1_Mid Common Delay Centre** The SKA1_Mid shall determine each dish and effective sub-array position in absolute terms (i.e. relative to the centre of the earth, not each other) to an accuracy of better than 1 cm. At each of these geographical reference positions the time will be traceable to the SKA timescale with an accuracy as specified by the Time stamping requirement.

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Allocation	SDP, TM

SKA1-SYS_REQ-3293	**SKA1_Mid common delay centre time** Each SKA1_Mid subarray shall have a common delay centre at or near its centre with a time accurate to the SKA timescale and a precision of better than 2ns (1σ) over periods of one observation and at least 10 years.
Allocation	CSP, TM, SADT

SKA1-SYS_REQ-2997	**SKA1_Mid subarray tied-array beam receptor exclusion** The SKA1_Mid shall assign dynamic weights to receptors within a subarray contributing to tied-array beams including the ability to exclude individual receptors.
Allocation	CSP, SDP, TM

SKA1-SYS_REQ-3525	**Coherence of SKA1_Mid tied-array beams** When commanded, SKA1_Mid shall form pulsar search, pulsar timing, and VLBI tied-array beams that each have a coherence within 5% of that allowed by the current atmospheric conditions.
Allocation	SDP, TM, CSP

SKA1-SYS_REQ-2847	**SKA1_Mid tied-array beams: store time-dependent dish weights** SKA1_Mid shall store the time-dependent dish weights used for each tied-array beam sum.
Allocation	CSP

4.3.4 VLBI beams

SKA1-SYS_REQ-2762	**SKA1_Mid VLBI S/N performance** The SKA1_Mid, when forming VLBI beams, shall have a signal-to-noise performance better than 90% of that achievable by an ideal signal chain, given the same inputs, instrumental calibration and excluding RFI.
Allocation	CSP, SADT
Proposed Allocation	CSP, ~~SADT~~
Rationale	This requirement is for Digital Signal Processing only. Discussed and agreed with SADT that should not be allocated to SADT.
Risk	Low

SKA1-SYS_REQ-2852	**SKA1_Mid VLBI configurability** SKA1_Mid, when commanded, shall change the pointing, centre frequency, and bandwidth of each VLBI tied-array beam independently, on scan boundaries.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Rationale	Discussed and agreed with SADT that should not be allocated to SADT.

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Risk	Low

SKA1-SYS_REQ-2854	**SKA1_Mid VLBI configurability** SKA1_Mid shall, when commanded, reconfigure the centre frequency, frequency band, and bandwidth for each tied-array beam, in less than 30 seconds.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Rationale	Discussed and agreed with SADT that should not be allocated to SADT.
Risk	Low

SKA1-SYS_REQ-2853	**SKA1_Mid VLBI independently configurable beams.** When commanded, SKA1_Mid shall form up to at least 4 separate VLBI tied-array beams up to a beams-bandwidth product of 10 GHz, distributed across one or more subarrays, each beam having independently configurable sky coordinates.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Rationale	Discussed and agreed with SADT that should not be allocated to SADT.
Risk	Low

SKA1-SYS_REQ-2689	**SKA1_Mid VLBI: number of beams** SKA1_Mid, when commanded, shall produce a total of up to four VLBI beams, spread across one or more subarrays.
Allocation	CSP, TM

SKA1-SYS_REQ-2851	**SKA1_Mid VLBI beamforming weights** SKA1_Mid, when commanded, shall weight the dish inputs into the VLBI tied-array sums based on relative sensitivity and coherence losses.
Allocation	CSP, TM, SDP

SKA1-SYS_REQ-2759	**SKA1_Mid VLBI: beamforming** SKA1_Mid, when commanded, shall generate VLBI beams from any or all receptors within a subarray which are separated by at most 100km.
Allocation	CSP, TM
Proposed Description	**SKA1_Mid VLBI array diameter** SKA1_Mid, when commanded, shall generate VLBI beams from any or all receptors within a subarray, that includes up to all dishes in the array.
Rationale	Clarified title. Allow beamforming with the whole array. SKA1-CSP_ASS-388
Risk	Low

SKA1-SYS_REQ-3469	**SKA1_Mid VLBI reference position** The SKA1_Mid VLBI array phase centre shall be within 100km of one of the

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	SKA1_Mid receptors.
Allocation	CSP, TM, SDP

SKA1-SYS_REQ-2855	**SKA1_Mid VLBI: spectral resolution** SKA1_Mid shall, when commanded, generate VLBI beams with a spectral resolution different from the spectral resolution used for imaging within the same subarray.
Allocation	CSP, TM

SKA1-SYS_REQ-2761	**SKA1_Mid VLBI beam bandwidth** The bandwidth for each SKA1_Mid VLBI beam shall be independently configurable, with a contiguous processing bandwidth up to the full bandwidth of the selected Band. For Band 5 this applies to each of the two 2.5 GHz streams, and not across streams -- that is, a single Band 5 VLBI beam can produce two 2.5 GHz - wide outputs.
Allocation	CSP, TM, SADT

4.3.5 VLBI beam-channels

SKA1-SYS_REQ-2849	**SKA1_Mid VLBI beams sampling rate** SKA1_Mid, when forming VLBI beams, shall output them with a sampling rate selectable between Nyquist and at least a factor of two oversampling for the selected bandwidth.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Mid VLBI beams sampling rate (Useful)** SKA1_Mid, when forming VLBI beams, shall output them with a sampling rate selectable between Nyquist and at least a factor of two oversampling for the selected bandwidth.
Rationale	Discussed and agreed with SADT that should not be allocated to SADT. Modern software correlators do not require oversampling. Classified as useful.
Risk	Low

SKA1-SYS_REQ-2859	**SKA1_Mid VLBI out-of-channel rejection** SKA1_Mid, when commanded, shall generate VLBI beams with a transition band that is monotonically decreasing from -3dB at the channel edge, to -60dB at a frequency offset from the centre frequency by the channel bandwidth.
Allocation	CSP, TM
Proposed Description	**SKA1_Mid VLBI out-of-channel rejection** SKA1_Mid, when commanded, shall generate VLBI beams channels with a transition band that is monotonically decreasing from -3dB at the channel edge, to -60dB at a frequency offset from the centre frequency by the beam channel

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	bandwidth.
Rationale	Clarified text referring to beam channels.
Risk	Low

SKA1-SYS_REQ-3474	**SKA1_Mid VLBI: spectral purity** Spectral distortion, after calibration, for SKA1_Mid VLBI shall be below: • -30dB in amplitude • 0.01 radians in phase
Allocation	CSP
Proposed Description	**SKA1_Mid VLBI: spectral purity** Spectral distortion of VLBI beams, after calibration, ~~for SKA1_Mid VLBI~~ compared to an ideal analogue beamformer provided with the same inputs, shall be below: • -30dB in amplitude • 0.03 radians in phase
Rationale	-30dB is 3% error in amplitude, a quadrature amplitude error of 3% introduces a phase error of 0.03 radians. Changed text, as for similar PSS and PST requirements. SKA1-CSP_ASS-313
Risk	Medium

SKA1-SYS_REQ-2760	**SKA1_Mid VLBI centre frequency** When commanded, for each VLBI beam, SKA1_Mid shall tune the centre frequencies of each of its derived beam channels independently with: • Beam channels of 128 MHz bandwidth or less, to an accuracy of 0.01 MHz or better, such that their bandwidth falls entirely within the fixed boundaries of beam channels greater than 128 MHz. • Beam channels of greater than 128 MHz bandwidth having fixed offset centre frequencies within the processed bandwidth of the observing Band.
Allocation	CSP, TM
Proposed Description	**SKA1_Mid VLBI centre frequency** When commanded, for each VLBI beam, SKA1_Mid shall tune the centre frequencies of each of its derived beam channels independently with: • Beam channels of 128 MHz bandwidth or less, to an accuracy of 0.01 MHz ~~or better~~, such that their bandwidth falls entirely within the fixed boundaries of beam channels greater than 128 MHz. • Beam channels of greater than 128 MHz bandwidth having fixed offset centre frequencies within the processed bandwidth of the observing Band, with a tuning accuracy of 0.01MHz.
Rationale	Added tuning accuracy for the frequency slices (SKA1-CSP_Mid_CBF_REQ-1857)
Risk	Low

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SKA1-SYS_REQ-2856	**SKA1_Mid VLBI beam channel sampled bandwidth.** SKA1_Mid, when commanded, shall generate VLBI beam channel data with a selectable channel width of: 128, 64, 32, 16, 8, 4, 2, 1 MHz, or a single wideband option, with channel width greater than (128 + 2n + 2m MHz) and less than or equal to 512MHz. Where n and m are non-negative integers.
Allocation	CSP, TM
Proposed Description	**SKA1_Mid VLBI beam channel sampled bandwidth.** SKA1_Mid, when commanded, shall generate VLBI beam channel data with a selectable channel width of: 128, 64, 32, 16, 8, 4, 2, 1 MHz, or a single wideband option, with channel width equal to 224MHz (200 MHz effective).
Rationale	Modified according to Mid capabilities [RD7], [RD9].
Risk	Low

SKA1-SYS_REQ-2845	**SKA1_Mid VLBI beam output data** SKA1_Mid shall be able to produce VLBI beam output data with either dual or single polarization.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Mid VLBI beam output data** SKA1_Mid shall be able to produce VLBI beam channel output data with either dual or single polarization.
Rationale	Discussed and agreed with SADT that should not be allocated to SADT. Clarified text referring to beam channels.
Risk	Low

SKA1-SYS_REQ-2846	**SKA1_Mid Word length of VLBI beam output data** SKA1_Mid shall be able to output VLBI beam data with configurable word formats, the allowed values being 2, 4, 8, and 16-bit integer.
Allocation	CSP, TM, SADT
Proposed Allocation	CSP, TM, ~~SADT~~
Proposed Description	**SKA1_Mid Word length of VLBI beam output data** SKA1_Mid shall be able to output VLBI beam channel data with configurable word formats, the allowed values being 2, 4, 8, and 16-bit integer.
Rationale	Discussed and agreed with SADT that should not be allocated to SADT. Clarified text referring to beam channels.
Risk	Low

4.3.6 Frequency standard and timescale

SKA1-SYS_REQ-3095	**SKA1_Mid VLBI Reference Frequency Stability** The SKA1_Mid timescales shall have a frequency stability, expressed as Allan Deviation, of at least: **AVERAGING TIME [S]** **STABILITY**

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	1	$2.0\ 10^{-13}$
	10	$5.0\ 10^{-14}$
	100	$1.3\ 10^{-14}$
	1000	$3.2\ 10^{-15}$
	floor up to 10^5	$3.0\ 10^{-15}$
Allocation	SADT	

SKA1-SYS_REQ-3292	**SKA1_Mid VLBI time stamping** Each SKA1_Mid VLBI data sample shall be directly traceable to the time at the common delay centre of the SKA1_Mid telescope, with an accuracy of better than 2 nanoseconds.
Allocation	CSP, SADT, DSH
Proposed Description	**SKA1_Mid VLBI time stamping** Each SKA1_Mid VLBI data sample shall be directly traceable to the time at the common delay centre of the SKA1_Mid telescope, with an accuracy of better than 0.05 microseconds.
Rationale	Discussed with VLBI SWG: constant offset of no more than 100 microseconds with accuracy better than 0.05 microseconds (per Mark5B experience).
Risk	Low

4.3.7 VLBI Terminal

SKA1-SYS_REQ-3138	**SKA1_Mid Standard VLBI formats** SKA1_Mid VLBI data shall conform to the SKA-VLBI ICD (to be written).
Allocation	TM
Proposed Allocation	TM, CSP
Proposed Description	**SKA1_Mid Standard VLBI formats** SKA1_Mid VLBI data shall conform to the SKA-VLBI ICD ~~(to be written)~~.
Rationale	Allocation to CSP as they produce the VDIF packets. SKA-VLBI ICD [RD9].
Risk	Low

SKA1-SYS_REQ-2838	**SKA1_Mid VLBI data sources** The SKA1_Mid telescope shall be a data source for VLBI data acquisition system. The interface between the SKA1_Mid telescope and the external VLBI data acquisition system will be compliant with the ICD SKA-TEL-SKO-0000116.
Allocation	INFRA, CSP, TM, SADT
Proposed Allocation	INFRA, CSP, TM, SADT, SDP
Rationale	Allocation to SDP for Mid as VDIF packets are fed via the SDP Ingress Ethernet switch [RD9], [RD6].
Risk	Low

SKA1-SYS_REQ-2841	**SKA1_Mid Infrastructure for VLBI equipment:** The following infrastructure shall be provided to allow eventual outfitting of

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	SKA1_Mid with VLBI equipment: 6. Adequate access for the potential fitment of VLBI equipment 7. Equipment space 8. Power 9. Cooling 10. Cable trays
Allocation	INFRA

SKA1-SYS_REQ-2843	**SKA1_Mid Compatibility with existing VLBI terminal** SKA1_Mid shall be able to output VLBI beam data with each individual stream limited to 512 MHz of signal bandwidth to ensure compatibility with existing VLBI terminal capability.
Allocation	CSP, SADT
Proposed Allocation	CSP, SADT, SDP
Rationale	Allocation to SDP for Mid as VDIF packets are fed via the SDP Ingress Ethernet switch [RD9], [RD6]. Existing VLBI terminal capability can accept > 512 MHz signal bandwidth [RD9].
Risk	Low

5 New L1 VLBI Requirements

This section of the document details the new set of requirements related to the VLBI capability within the Level 1 requirements for consideration within the context of the ECP submission.

It should be noted that the issued requirements [AD1] take precedence and that the new requirements listed below are for convenience only. Any potential review by a CRB should consider them in terms of completeness.

This section is structured in three subsections: SKA1 Common VLBI requirements, SKA1-LOW VLBI specific requirements and SKA1-MID VLBI specific requirements. Each subsection is divided in topics, e.g. requirements for tied-array beams, VLBI beams, VLBI beam-channels, etc.

5.1 SKA1-COMMON Requirements

5.1.1 Observing modes and Commensality

NEW	**VLBI Observing** On command, SKA1_Low and SKA1_Mid shall configure to support VLBI observing as a

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	constituent member of a Global VLBI network.
Rationale	From OCD Rev 3 [RD8]
Risk	Low

NEW	**VLBI Observing Modes** On command, SKA1_Low and SKA1_Mid shall configure to support VLBI observing in standard mode (record/playback) or in e-VLBI mode.
Rationale	From OCD Rev 3 [RD8]. Expected latencies with the external correlator are about 330 ms, that is the currently experienced latency from New Zealand to The Netherlands.
Risk	Low

5.1.2 Scheduling

NEW	**VLBI Observing Projects** SKA1_Common shall accept VLBI Observing projects for the SKA, ingesting and parsing the VLBI standard VEX file to create a Scheduling Block for SKA VLBI observing with SKA1_Low or SKA1_Mid.
Rationale	From OCD Rev 3 [RD8]
Risk	Low

NEW	**VLBI Observing Projects Updates** SKA1_Common shall accept updates to existing SKA VLBI observing projects by ingesting and parsing a VLBI standard VEX file and updating the associated Scheduling Block for SKA VLBI observing with SKA1_Low and SKA1_Mid.
Rationale	From OCD Rev 3 [RD8]
Risk	Low

5.1.3 Tied-array beams

NEW	**Tied array beams from subarrays** The SKA1_Mid and SKA1_Low, when commanded, shall form tied-array beams from subarrays
Rationale	From OCD Rev 3 [RD8]
Risk	Low

NEW	**Direction-dependent corrections for beamforming (useful)** The SKA1_Mid and SKA1_Low shall apply direction-dependent corrections for beamforming.
Rationale	Discussions with VLBI SWG group: The calibration terms for the antennas will need to be fed back to the correlator in both real time and for the directions of the tied array beams. Plans are in hand for

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	direction independent calibration (RCAL), but the difference from that solution (for source flux-weighted average dTEC over the array) to that for the specific tied array beam directions has not been addressed. This will be a greater issue for SKA1-LOW than for SKA1-MID, but does apply for both. For distances less than 5km (the core in SKA-LOW (SKA-TEL-SKO-DD-001)) the MWA data suggest that the assumption of a low-order dTEC surface over the array is acceptable for >90% of directions and times (as per SKA1-SYS_REQ- 2762). This will require confirmation in a wider range of weathers. In relation with REQ-3529 Ionosphere calibration interval
Risk	Medium

5.1.4 VLBI beams

No new requirements for SKA1-Common are needed for this topic.

5.1.5 VLBI beam-channels

No new requirements for SKA1-Common are needed for this topic.

5.1.6 Frequency standard and timescale

NEW	**Steering to UTC for VLBI** The SKA1_Mid and SKA1_Low, when commanded, shall have the ability to disable steering to UTC during VLBI observations.
Rationale	SWG discussions
Risk	Medium

5.1.7 VLBI Terminal

NEW	**VLBI equipment internet access** The SKA1_Mid and SKA1_Low shall allow internet access to/from the VLBI Terminal to the external correlator.
Rationale	Requirement on SPC INFRA SKA to VLBI ICD [RD9]
Risk	Low

NEW	**VLBI Terminal Monitor and Control** The SKA1_Mid and SKA1_Low shall monitor and control the VLBI Terminal during VLBI observations.
Rationale	SWG discussions, TM CDR outcomes TM to VLBI ICD [RD3]
Risk	Low

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5.2 SKA1-LOW Requirements

5.2.1 Observing modes and Commensality

No new requirements for SKA1-LOW are needed for this topic.

5.2.2 Scheduling

No new requirements for SKA1-LOW are needed for this topic.

5.2.3 Tied-array beams

NEW	**SKA1_Low tied-array beams: store time-dependent station weights** SKA1_Low shall store the time-dependent station weights used for each tied-array beam sum.
Rationale	Equivalent requirement as for Mid, as a result of RFI flagging. This information needs to be included in the metadata for the External VLBI correlator [RD3].
Risk	Medium

NEW	**SKA1_Low: Tied array beams constrained to a single station beam** For a given tied array beam (PSS, PST or VLBI), SKA1_Low shall include input data from only one of the station beams produced by each station included in the sub-array.
Rationale	SKA1-CSP-ASS-438
Risk	Low

NEW	**SKA1_Low multi-beam simultaneity** When commanded, independently for each subarray, SKA1_Low shall simultaneously perform 1. Generation of visibilities either standard or zoom 2. Pulsar Search 3. Pulsar Timing 4. Dynamic Spectrum 5. Transient Search 6. VLBI in each station beam of that subarray. Subject to limitation imposed by other requirements and the condition that there is sufficient imaging sensitivity for calibration of beams.
Rationale	SKA1-CSP-ASS-163
Risk	Low

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5.2.4 VLBI beams

No new requirements for SKA1-LOW are needed for this topic.

5.2.5 VLBI beam-channels

NEW	**SKA1_Low number of beam-channels per VLBI beam** SKA1_Low, when commanded, shall form up to 4 dual-polarization beam-channels per VLBI beam.
Rationale	From CSP Low to VLBI ICD [RD2] SKA1-CSP_ASS-432
Risk	Low

NEW	**SKA1_Low VLBI beam-channels bandpass ripple** For any SKA1_Low VLBI beam-channel, and for a spectrally flat, broadband input to the beamformer, the peak-to-peak variation in signal-to-noise ratio across the beamformed bandwidth, for any output word size, shall be no more than 2%.
Rationale	SKA1-CSP_ASS-428 same assumption for Low than for Mid
Risk	Medium

NEW	**SKA1_Low VLBI beam-channel frequency response** For any SKA1_Low VLBI beam-channel, and for a spectrally flat, broadband input to the beamformer, the beamformed bandwidth shall have a frequency response which: 1. has a phase response varying by no more than 0.05 radians peak-to-peak, and 2. has an amplitude response varying by no more than 0.1 dB peak-to-peak.
Rationale	SKA1-CSP_ASS-427 same assumption for Low than for Mid
Risk	Medium

NEW	**SKA1_Low VLBI beam-channel temporal impulse response** When commanded, SKA1_Low shall produce VLBI beam-channels with temporal impulse responses that are at worst the inverse Fourier transform of their beam-channel frequency responses.
Rationale	SKA1-CSP_ASS-291 same assumption for Low than for Mid
Risk	Medium

NEW	**SKA1_Low VLBI beam channel output real representation** SKA1_Low VLBI beam channel outputs shall be real sampled data.
Rationale	Discussions with VLBI SWG SKA1-CSP_ASS-393 same assumption for Low than for Mid
Risk	Low

NEW	**SKA1_Low VLBI beam channel power level** SKA1_Low shall measure and report VLBI beam channels averaged power levels and internal gain settings.
Rationale	Discussions with VLBI SWG [RD2].

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Risk	Low

NEW	**SKA1_Low VLBI beam channel RFI flagging** When commanded, SKA1_Low shall produce VLBI beam channels RFI flagged at the station beam fine channel resolution.
Rationale	Discussions with VLBI SWG SKA1-CSP_ASS-389 equivalent for Low [RD2].
Risk	Low

NEW	**SKA1_Low VLBI beam polarization calibration** When commanded, SKA1_Low shall apply polarization calibration corrections to each VLBI beam before output.
Rationale	Discussions with VLBI SWG SKA1-CSP_ASS-395 equivalent for Low [RD2].
Risk	Low

5.2.6 Frequency standard and timescale

No new requirements for SKA1-LOW are needed for this topic.

5.2.7 VLBI Terminal

NEW	**SKA1_Low: Noise power reporting interval** When commanded, independently for each subarray, SKA1_Low shall measure and report the average power levels for each field station, with a configurable measurement interval as short as the shortest possible visibility integration period, and a configurable reporting interval which is any integer multiple of that measurement interval.
Rationale	SKA1-CSP_ASS-282 same assumption for Low than for Mid Metadata for external correlator. TM to VLBI ICD [RD3].
Risk	Low

5.3 SKA1-MID Requirements

5.3.1 Observing modes and Commensality

No new requirements for SKA1-MID are needed for this topic.

5.3.2 Scheduling

No new requirements for SKA1-MID are needed for this topic.

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5.3.3 Tied-array beams

No new requirements for SKA1-MID are needed for this topic.

5.3.4 VLBI beams

No new requirements for SKA1-MID are needed for this topic.

5.3.5 VLBI beam channels

NEW	**SKA1_Mid number of beam channels per VLBI beam** SKA1_Mid, when commanded, shall form up to 4 dual-polarization beam channels per VLBI beam.
Rationale	From CSP Mid to VLBI ICD [RD1].
Risk	Low

NEW	**SKA1_Mid VLBI beam channel bandpass ripple** For any SKA1_Mid VLBI beam channel, and for a spectrally flat, broadband input to the beamformer, the peak-to-peak variation in signal-to-noise ratio across the beamformed bandwidth, for any output word size, shall be no more than 2%.
Rationale	SKA1-CSP_ASS-428
Risk	Medium

NEW	**SKA1_Mid VLBI beam channel frequency response** For any SKA1_Mid VLBI beam channel, and for a spectrally flat, broadband input to the beamformer, the beamformed bandwidth shall have a frequency response which: 1. has a phase response varying by no more than 0.05 radians peak-to-peak, and 2. has an amplitude response varying by no more than 0.1 dB peak-to-peak.
Rationale	SKA1-CSP_ASS-427
Risk	Medium

NEW	**SKA1_Mid VLBI beam channel temporal impulse response** When commanded, SKA1_Mid shall produce VLBI beam channels with temporal impulse responses that are at worst the inverse Fourier transform of their beam-channel frequency responses.
Rationale	SKA1-CSP_ASS-291
Risk	Medium

NEW	**SKA1_Mid VLBI beam channel output real representation** SKA1_Mid VLBI beam channel outputs shall be real sampled data.
Rationale	Discussions with VLBI SWG SKA1-CSP_ASS-393
Risk	Low

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NEW	**SKA1_Mid VLBI beam channel power level** SKA1_Mid shall measure and report VLBI beam channels averaged power levels and internal gain settings.
Rationale	Discussions with VLBI SWG [RD1]
Risk	Low

NEW	**SKA1_Mid VLBI beam channel amplitude RFI-flagging invariant** When commanded, SKA1_Mid shall produce VLBI beam channels RFI flagged at the 220MHz resolution, with amplitudes that are RFI-flagging invariant.
Rationale	Discussions with VLBI SWG [RD1] SKA1-CSP_ASS-389
Risk	Low

NEW	**SKA1_Mid VLBI beam polarization calibration** When commanded, SKA1_Mid shall apply polarization calibration corrections to each VLBI beam before output.
Rationale	Discussions with VLBI SWG [RD1] SKA1-CSP_ASS-395
Risk	Low

NEW	**SKA1_Mid VLBI per-antenna, per-beam polarization calibration (Useful)** When commanded, SKA1_Mid shall apply frequency- dependent (with at least 1 MHz resolution), per-antenna, per-beam polarization calibration corrections, prior to VLBI beamforming.
Rationale	Discussions with VLBI SWG [RD1] SKA1-CSP_ASS-318
Risk	Low

NEW	**SKA1_Mid VLBI beam channel polarization calibration (Useful)** When commanded, SKA1_Mid shall apply polarization calibration corrections to each VLBI beam channel individually before output.
Rationale	Discussions with VLBI SWG [RD1] SKA1-CSP_ASS-292
Risk	Low

5.3.6 Frequency standard and timescale

NEW	**SKA1_Mid Sample Clock Frequency Offset for VLBI** SKA1_Mid shall be able to apply same sample clock frequencies for each dish during VLBI observations.

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Rationale	Discussions with VLBI SWG
Risk	Medium

5.3.7 VLBI Terminal

NEW	**SKA1_Mid: Noise power reporting interval** When commanded, independently for each subarray, SKA1_Mid shall measure and report the average power levels for each receptor, separately for the noise diode ON and noise diode OFF conditions, with a configurable measurement interval as short as the shortest possible visibility integration period, and a configurable reporting interval which is any integer multiple of that measurement interval.
Rationale	Discussions with VLBI SWG Metadata for external correlator. TM to VLBI ICD [RD3]. SKA1-CSP_ASS-282
Risk	Low

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ANNEX 4: SKA1 Critical Design Reviews Outcomes for the VLBI Capability

ANNEX 4.1 SKA1 Central Signal Processor MID Correlator and Beamformer Sub-element

This CDR took place on 5-7 March 2018.

The MID.CBF team presented the Frequency Slice Architecture (FSA) architecture that minimises complexity, partitioning the processing into components that provides all necessary functionalities in parallel. The design uses just one LRU type for all FPGA processing and was supported by sufficient prototyping and testing.

With respect to the VLBI capability it is well captured, surpassing the required functionality as MID.CBF can provide up to 520 VLBI beams of 200MHz bandwidth each in up to 16 subarrays, with up to 2080 dual-polarization tuneable real channels in total. The beamformer performs RFI flagging and excision and polarization calibration at the 200MHz level. The FSA architecture is quite flexible, allowing commensal observing in the different bands, and the VLBI capability provides simultaneous beams and low frequency resolution visibilities regardless of commensality with other modes. The FSA architecture is scalable to allow a possible extension to support 20% more antennas without major effort, with baselines up to several thousands of km.

Some aspects with respect to the VLBI capability that need to be improved or were discussed during the review are the following:

- Commensality comes with a bandwidth sacrifice due to the limited hardware resources but fulfils the L1 requirements.
- The choice of 200 MHz frequency slices is not the most appropriate to be compatible with other VLBI observatories, but compatibility will be achieved using narrower beam-channels.
- The issue of how to represent the beam-channels was resolved before the CDR, and the decision was made that the design will include a Hilbert transform to provide real representation.
- Measurement and logging of power levels and internal gain settings for each beam-channel included at CDR.
- Topocentric doppler correction for beamforming, without correction for the target, was resolved at the CDR.
- Mid will provide only Nyquist sampling for the VLBI channels, although the L1 requirement ask for oversampling. As oversampling is not needed with modern software correlators, the L1 requirement will be amended.
- One VLBI L2 requirement does not flow down to L3, i.e. beam channel output word size 2,4,8 and 16 bits, but the design is compliant.
- The design is not compliant with 3 VLBI beam polarization calibration requirements (classified as useful, not essential), but the basic polarization correction is in place at the Frequency Slice

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level (there are insufficient FSP FPGA resources to perform Jones Matrix correction for each beam-channel, each receptor/beam or frequency dependent, per-receptor, per-beam).
- There is one VLBI L2 assumption: to allow for an offset between the VDIF timestamp and the CSP_MID UTC epoch.

As a result of this review the missing CSP MID to VLBI ICD has been written and signed (Annex 2.2).

ANNEX 4.2 SKA1 Central Signal Processor LOW Correlator and Beamformer Sub-element

This CDR took place on 8-9 March 2018.

The LOW.CBF team presented a detailed description of the design, development, prototyping and testing of a viable implementation of a correlator and beamformer for the SKA1-LOW telescope.

With respect to the VLBI capability it is well captured, providing the required functionality. As VLBI beams are produced in the same way as Pulsar Timing beams, up to 16 Pulsar Timing and VLBI beams are available in total. VLBI beams LOW.CBF architecture allows commensal observing for all modes within the same subarray.

Some aspects with respect to the VLBI capability that need to be improved or were discussed during the review are the following:

- Signal processing firmware prototyping for VLBI implementation on GPU/CPUs needs to be undertaken.
- There are 6 VLBI L2 requirements that do not flow down to L3, but the design is compliant.
- The issue of how to represent the beam-channels was resolved before the CDR, and the decision was made that the design will include a Hilbert transform to provide real representation.
- Low will provide oversampling for the VLBI channels, fulfilling the L1 requirements.
- Topocentric doppler correction for beamforming, without correction for the target, was resolved at the CDR.
- Low VLBI beams with 256MHz maximum bandwidth per polarization, with 4 dual-polarization channels per beam.
- Certain VLBI configurations (longest baselines and lowest frequencies) fail the requirement for maximum phase slope for off-axis beamforming.
- RFI excision and flagging details were found to be immature.
- Measurement and logging of power levels for each beam-channel included at CDR.

As a result of this review the missing CSP LOW to VLBI ICD has been already written and signed (Annex 2.1).

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ANNEX 4.3 SKA1 Telescope Manager Element

This CDR took place on 17-20 April 2018.

Enormous progress has been made since the Preliminary Design Review, the TM team presented a set of System Architecture Documents of very high quality, with continued focus on commissioning and engineering tools as part of system design and not only for steady state operations.

With respect to the VLBI capability an extensive review of TM VLBI L2 and L3 requirements has been conducted, 33 Observation Action Register (OARs) were raised mostly against VLBI requirements and details within the documentation, outlining incorrect definitions, unclear concepts, etc. These include:

- Description of FSP VLBI capabilities in the documentation.
- TM requirements to configure CSP for VLBI with missing parameters.
- TM requirement for commensal observing in a subarray were incorrect. For SKA1-LOW, commensality needs to include VLBI.
- Scan boundaries defined in the L1 requirements do not properly flow down to L2.
- Four VLBI beams can be formed from the same subarray, not only using different subarrays. The verification of this requirement was not appropriate.
- Use of UTC for VLBI observations instead of LST and local time.
- The ICD for the TM Interface with the VLBI terminal is missing.
- Use VDIF instead of VSI protocol.

Most of the observations were resolved during the CDR meeting, but a discussion was scheduled with TM and CSP consortia (16/04/2018) to discuss and solve open issues about the VLBI requirements and to draft and sign the missing TM to VLBI ICD document, including a Tango framework description for the VLBI terminal (Annex 2.3).

ANNEX 4.4 SKA1 Signal and Data Transport Element

This CDR took place on 15-18 May 2018.

An impressive design effort was demonstrated, with no technical showstoppers identified incorporating state-of-the-art techniques to provide a robust solution that fulfils the different SKA scientific requirements, including VLBI.

With respect to the VLBI capability, the reviewed compliance matrix and L2/L3 requirements for VLBI found:

- Several VLBI L1 requirements did not properly flow down to L2/L3s
- There are missing non-science data network (NSDN) L3 requirements for certain VLBI SaDT L2 requirements

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- Some wording amendments need to be made to VLBI L3 requirements, apropos the VLBI terminal location.

After the CDR meeting a discussion was scheduled with the SaDT Consortium (27/06/2018) to discuss and solve open issues and to draft the missing SaDT to VLBI ICD document. Another meeting was held with SaDT Consortium (2/10/2018) for clarification on the non-science data network (NDSN) connection for the VLBI Terminal. The SaDT (Mid and Low) to VLBI ICD documents are attached to this deliverable in a draft form (Annex 2.4 and 2.5).

ANNEX 4.5 SKA1 Science Data Processor Element

This Preliminary CDR took place on 19-22 June 2018.

The goals of this review were to understand the risks to System CDR and to assess the architecture as it stands, to provide guidance for development between the review date and CDR, currently scheduled for January 2019.

With respect to the VLBI capability 8 OARs were raised, outlining improperly flowed down or missing requirements, incorrect definitions, clarifying concepts, etc.

After the pre-CDR meeting a discussion was scheduled with SDP Consortium (15/08/2018) to discuss and solve open issues about the VLBI requirements for SDP. The missing SDP to VLBI ICD document will be produced for the element CDR (January 2019), and is attached to this deliverable in draft form (Annex 2.6).

ANNEX 4.6 SKA1 Central Signal Processor Local Monitoring and Control sub-element

This CDR took place on 24 September 2018.

The CSP Local Monitoring and Control (LMC) submission presented a detailed description of the design, development, prototyping and testing of a viable implementation of the CSP LMC, for the SKA1 Mid and SKA1 Low telescopes.

With respect to the VLBI capability 28 OARs were raised.

Different aspects of the configuration of the MID correlator to perform a VLBI observation were discussed such as the configuration and control of the VLBI beams within each subarray. Complete configuration independence is not achievable as only one VLBI scheduling block (describing a set of successive scans) is executed in each subarray at a time. An appropriate approach will have to be agreed for each observation.

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The Internal LMC to other CSP sub-elements ICD was updated to include necessary VLBI metadata.

ANNEX 4.7 SKA1 Central Signal Processor Element

This CDR took place on 25-28 September 2018.

Once all CSP sub-elements were reviewed, the design and requirements were assessed at the element level.

With respect to the VLBI capability 28 OARs were raised mostly against LMC VLBI requirements (10) with the rest pointing to VLBI details in the documentation.

VLBI beamforming aspects for LOW Correlator were discussed, such as the possibility to beamform using LFAA substations to access larger FoV for transient localisation.

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