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JUMPING JIVE

Project ID: 730884

WP10: VLBI with the SKA

Deliverable:	D10.2 Operational Model for inclusion of SKA in Global VLBI
Lead beneficiary:	JIV-ERIC and Square Kilometre Array Phase 1 Project
Submission date:	15/6/2020
Dissemination level:	SKA Organisation Operations Planning Group, JIV-ERIC Institute

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1 Executive Summary

In preparation for the construction of the Phase 1 of the SKA Observatory two key documents are being prepared that will be submitted to the SKA Council for approval: the SKA1 Construction Proposal and the SKA1 Operations Plan. The latter will include a description of the science and engineering operations required to support the VLBI capability in the SKA Phase 1 Observatory (SKA-VLBI in what follows), and the mechanisms to access the data and resources.

The EC Horizon 2020 JUMPING JIVE project with its work package 10 (WP10) "VLBI with the SKA" has already contributed to the definition of the SKA-VLBI capability presenting a design for the VLBI equipment that would be required for the SKA telescopes, with a detailed description of its interfaces and requirements (deliverable D10.1, RD01). It has also presented a portfolio of science cases (deliverable D10.3, RD02) prepared by the SKA VLBI science working group members, that has demonstrated the capabilities and observing strategies required to support the different use cases. Lastly, WP10 has organised a workshop on SKA-VLBI Key Science Projects and Operations (https://indico.skatelescope.org/event/539/) where more than 20 scientists presented a wide variety of transformational science that can be achieved with the SKA-VLBI capability and culminated with discussions among all the participants organised in different groups on how to realise SKA-VLBI Key Science Projects (deliverable D10.4, in preparation).

This deliverable D10.2 "Operational Model for inclusion of SKA in Global VLBI" presents a draft model for the SKA-VLBI operations. For the model preparation, the identified constraints from previous WP10 work have been taken into account. These outcomes have been complemented by a comprehensive study of different VLBI networks operational models and a discussion of the SKA Operational Plan aspects that are relevant for VLBI operations. The different areas that would need discussion and/or agreement for inclusion of SKA in VLBI observations are pointed out.

The model presented in this document assumes the existence of a SKA-VLBI Consortium formed by VLBI networks and observatories that will commit to joint collaboration with the SKA, by develop and provide the VLBI equipment, and support its operation. This Consortium will also assist with the coordination of the different facilities for joint observations with the SKA.

This deliverable will be used as a starting point for future discussions between the different stakeholders for the establishment of the necessary agreements and for the elaboration of the definitive SKA1 Operations Plan by the SKA Observatory.

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2 Introduction

This document presents a model for the inclusion of the SKA1 telescopes in global Very Long Baseline Interferometry (VLBI) observations, describing the science and engineering operations for the VLBI capability in the SKA Phase 1 Observatory (SKA-VLBI), and the mechanisms to access the data and resources. These mechanisms will enable the implementation of high-level policies and agreements between the different stakeholders.

The present JUMPING JIVE deliverable lays the foundation for the elaboration of an SKA-VLBI Operational Model. At the time of writing, the SKA Observatory policies are being defined and agreed with the SKA Member nations, and agreements between the different VLBI networks and stakeholders will continue to evolve up until the SKA1 becomes operational, after construction completion. This document identifies areas that need consideration, discussion and agreement to support the SKA-VLBI capability.

The study presented in this deliverable has been structured in the following way: Firstly, Section 3 presents the operational models for the largest established VLBI networks, and the agreements currently in place for their collaboration. To complement the study the agreements for multi-frequency and multi-messenger observations are also presented. From the study of these different VLBI operational models, a list of issues that would need consideration for the SKA-VLBI capability have been extracted. Secondly, Section 4 summarises the Operational model for the SKA1 Observatory [RD03] and its implications for SKA-VLBI operations. Finally, Sections 5 and 6 present the operational implications derived from the study of SKA-VLBI science cases [RD02] and from the discussions held during the SKA-VLBI Key Science Projects and Operations workshop (October 2019, https://indico.skatelescope.org/event/539/). A draft of a SKA-VLBI Operational Model has been elaborated and is presented in Section 7.

This deliverable assumes that a SKA-VLBI Consortium will be established whose main functions will be to provide the VLBI equipment for the SKA telescopes and assist the coordination of VLBI Networks for joint observations with the SKA. This Consortium may comprise radio observatories and VLBI networks interested in observations with the SKA1 telescopes (SKA1-MID and SKA1-LOW) in their respective frequency ranges, and will necessarily have representation from the SKA Observatory. Coordination between the VLBI networks will be based on the long-proven model adopted nowadays for VLBI global observations. This collaboration with the SKA will necessarily imply some costs for the Consortium. The different VLBI stakeholders will properly define the scope, responsibilities and associated costs for the SKA-VLBI Consortium. The existence of this consortium will not prevent other agreements between the SKA and the VLBI networks.

In parallel to these agreements, a Global VLBI Alliance is currently being envisioned to foster a truly global collaboration for VLBI, to prepare the networks for the current and future challenges in the multi-wavelength and multi-messenger landscape. The alliance may serve

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as a focal point to share information among the VLBI networks and make sure that the different processes are kept compatible (backends, standards, correlation, etc.). It may also promote radio astronomy and VLBI in countries or regions where there is no such expertise. The Global VLBI Alliance is not required to support the SKA-VLBI Consortium, but it may certainly promote it.

2.1 Introduction to the SKA-VLBI Capability

The SKA-VLBI capability allows the inclusion of the SKA Phase 1 telescopes in VLBI observations (Paragi et al. 2015, RD09; Garcia-Miro et al. 2019, RD07). The SKA1 Observatory will be a novel multi-beam radio telescope. Both SKA1 telescopes will provide up to 4 VLBI beams, produced within a subarray of SKA1-MID antennas or SKA1-LOW stations (i.e. core partitions). Typically, this subarray will be formed from the inner core of each array, with a radius, chosen from a set of templates, defined as a trade-off between the VLBI beams' field of view and sensitivity. The signal from the antennas or stations from the subarray is phased-up coherently to form the different VLBI beams, with subarray sizes ultimately limited by the beamforming stability. The phasing characterisation and calibration will be determined during the SKA1 Commissioning phase.

For VLBI projects requiring broadband or simultaneous observations in different SKA bands, VLBI beams may be produced from up to 4 subarrays with similar resolution and sensitivity. To better utilise the SKA resources for some configurations, it may also be advantageous for VLBI experiments to use a core subarray for narrow VLBI beams plus several individual SKA antennas or stations that provide short uv-spacings to the VLBI network. Each of these elements is treated as a one-element subarray with the VLBI beam effectively providing the primary beam of the MID antenna or LOW station. Different SKA subarray templates will be defined to help with the design of the observations. These templates will have stable phase centres, with positions and times referred to the ITRF and the UTC, respectively. The SKA Observatory will regularly track the subarrays phase centres positions and velocities due to continental drift.

The VLBI beams produced from one or different subarrays can be controlled independently, with different pointings on the sky. Polarisation corrected and RFI masked VLBI beam voltage data is recorded in standard VDIF format, for inclusion in either real-time (electronic-VLBI or e-VLBI) or post-observation VLBI correlation. The standard VLBI channels bandwidths are available up to 64 MHz for LOW and 128 MHz (and the non-standard 200 MHz) for MID. The total observed bandwidth for the LOW beams is 256 MHz per polarisation, covering most of the band, while for MID the maximum bandwidth is 5 GHz per polarisation for 2 beams, or 2.5 GHz for 4 beams. Although the SKA System level requirements limit the number of VLBI beams to 4 for each telescope, the SKA design is capable of providing many more. The SKA1-MID telescope can provide more beams but with decreasing sensitivity, up to a maximum of 52 beams per subarray each with 200 MHz bandwidth, per polarisation. The SKA1-LOW

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telescope may also be able to provide up to a maximum of 16 VLBI beams, but with associated costs. The portfolio of SKA-VLBI science cases [RD02] has demonstrated the need for more VLBI beams than the 4 initially planned.

The SKA-VLBI capability is completely integrated into the SKA operational model as one of the standard observing modes of the SKA telescopes (Figure 1). Once a VLBI proposal is approved, the VEX file prepared by the Principal Investigator (PI) is processed by the Telescope Manager to generate SKA Scheduling Blocks (SB) with all the required telescope configuration information, including scheduling to observe at appropriate times. The correlator (Central Signal Processor, CSP) processes data from each of the configured subarrays and provides the subarray correlated visibilities to the Science Data Processor (SDP), located at the Science Processing Centre (SPC). The SDP processes the visibilities to produce the image cubes and sends back, in real-time, the beamforming calibration parameters to the correlator for coherent beamforming. The correlator produces the VLBI beams formatted in VDIF packets that are sent to a VLBI terminal, also located at the SPC facility and monitored and controlled as any other SKA subsystem. It will operate in standard record/playback mode or in e-VLBI mode for real-time data streaming and correlation. No physical shipment of data disks will be required for SKA-VLBI.

The SKA-VLBI capability will also provide SKA local interferometer imaging from the same subarray that is used to phase-up the VLBI beams. The SKA images are needed for calibration purposes and/or complementary science. Some projects may also need SKA polarization and spectral imaging, and pulsar and transient data, with the caveat that concurrent observing modes for the MID telescope is limited by its processing resources. The PI will access the final products from the designated VLBI correlator (i.e. VLBI visibilities) and the SKA products from the SKA Regional Centres.

The SKA1 Baseline Design [RD04] covers most of the above processes, however the VLBI equipment is expected to be provided by an external entity, here assumed to be the SKA-VLBI Consortium. A detailed description of the SKA-VLBI capability and the VLBI equipment necessary for its support, including hardware and software, was presented in the JUMPING JIVE deliverable “Details on VLBI Interfaces to SKA Consortia” [RD01]. The SKA-VLBI Consortium would also need to equip the VLBI correlators with the appropriate buffer to temporarily store the SKA VLBI data until the correlation takes place. Necessarily, the VLBI correlators’ software would need to be adapted to support multi-beam instruments such as the SKA.

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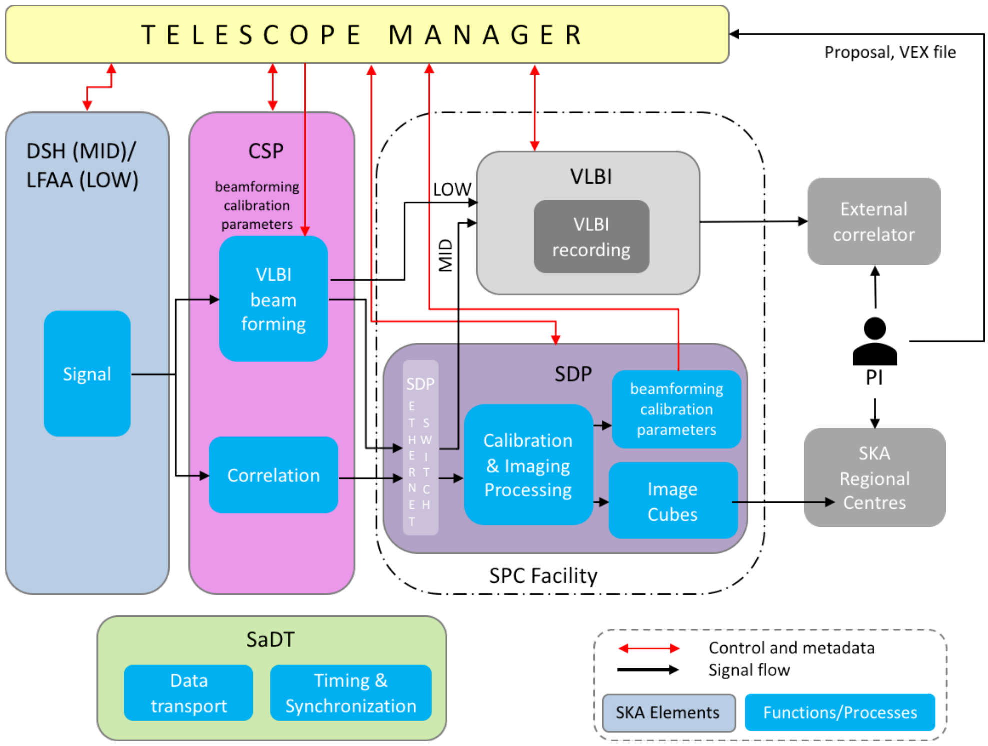

Figure 1. SKA-VLBI Capability for the SKA1 Observatory

3 VLBI Operational Model

This section summarises the operational models used by the largest established VLBI networks: the Australian Long Baseline Array (LBA), the European VLBI Network (EVN), the East Asian VLBI Network (EAVN), and the Very Long Baseline Array (VLBA). It also describes how phased-up interferometers, such as the Karl G. Jansky Very Large Array (VLA), Australia Telescope Compact Array (ATCA), and the Atacama Large Millimeter/submillimeter Array (ALMA), join VLBI observations. It is worth mentioning the Westerbork Synthesis Radio Telescope (WSRT) which is no longer operating in tied array mode for VLBI, but the experiences from joint operations with the EVN have greatly influenced the science case and the initial requirements for SKA-VLBI. The different agreements that the networks use to coordinate with each other for global VLBI observations and for multi-frequency and multi-messenger observations, and the implications these models and agreements may have for the SKA-VLBI operational model are also discussed.

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3.1 VLBI Networks Operational Models

While the principles are similar, the details of the operational models of VLBI Networks, and the rules by which tied-array components (ATCA, VLA and ALMA) are included in observations, are different. It is worthwhile considering the existing examples to arrive at an operational model that would fit SKA-VLBI. Table 1 describes details about Observatory Science Operations regarding access, proposal types, announcements of opportunity, observing cycles, proprietary periods, etc. Table 2 describes other aspects of science operations and technical information, such as observing modes, phasing requirements, calibration, correlation details, etc. For comparison, the tables also include information about SKA1 as a VLBI element, with current assumptions and To-Be-Decided (TBD) topics (red font). For a detailed description of the different VLBI operational models, refer to Annex 1.

Current VLBI facilities operate under a range of models; some are dedicated VLBI arrays that belong to just one institution, such as the Very Long Baseline Array (VLBA), the Korean VLBI Network (KVN), and the VLBI Exploration of Radio Astrometry (VERA) telescope. Others are composed of different observatories, each with their own observing program, that need to have agreements in place for collaboration within a VLBI network. Examples of the latter are the European VLBI Network (EVN), the East-Asia VLBI Network (EAVN), the Australian Long Baseline Array (LBA), the Global mm-VLBI Array (GMVA) and the Event Horizon Telescope (EHT). The VLBA, the EVN and the LBA are the only networks that include connected-element interferometer components routinely in their observations (in case of the EVN, due to the WSRT-Apertif upgrade this is currently not available). The VLBA occasionally joins with the VLA and other telescopes to form the High Sensitivity Array (HSA), and ALMA is a fundamental element to the GMVA and the EHT, although it is only available two weeks per year for VLBI. These observatories join VLBI observations under special arrangements. The most relevant to SKA-VLBI are the EVN, VLBA, EAVN, and the LBA operations because of the similar frequency coverage and global distribution. Another relevant example is global VLBI, where the major VLBI networks join to carry out particular observations.

In general, all VLBI networks are open skies facilities and they collaborate on these terms, with access based on the scientific merit and technical feasibility of proposals (Table 1). But they offer a limited amount of sky time during the observing cycles due to inherent availability. This availability could be limited due to whole network commitments (e.g. the VLBA offers only half of total time per year for astronomy projects), agreements between the members (e.g. the EVN observes between 60-80 days/year and the EAVN and the LBA 21 days/year) or due to individual array element commitments (e.g. the GBT dedicates part of its time to private projects). The connected interferometers chosen as examples here participate on different terms. VLA and ATCA participation is subject to proposal pressure with no time caps for VLBI but ALMA reserves a fixed amount of time for VLBI, about 5% of their total time available for science, allocated based on scientific merit.

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Most VLBI networks accept regular and time critical proposals (either triggered or Target of Opportunity). Triggered proposals are assessed by the TACs as regular proposals and approved with certain rules (trigger event definition and cadence, expiration date, etc.). Target of Opportunity (ToO) proposals are usually sent by e-mail to the network (with some exceptions) and are promptly assessed by the facilities. The response for ToOs is at least one day but typically up to a few days or even more. The EVN has implemented a scheme in which projects with high priority can be executed within 24h of a trigger if it occurs during/before a scheduled real-time e-EVN observation. The basic procedure for automated EVN triggering of projects on even shorter timescales (order of 10 minutes) has been worked out but is not operational yet. The VLBA and the VLA respond to time critical proposals, but not as part of the HSA. Similarly, ALMA does not consider time critical proposals for VLBI.

The proposal handling tools, announcement of opportunity deadlines, TAC processes and observing cycles are different for all observatories, adapted to their different characteristics and needs. Most of the networks have an observing cycle divided into two semesters, each with a proposal call, but the observing cycles and calls do not coincide (Figure 2). Conversely, the EVN has 3 proposal calls and a more complicated observing cycle with 3 observing sessions per year and the possibility to perform ten 24h real-time-correlation observations (e-VLBI) and ten additional observations outside of the normal observing sessions per year. The connected interferometers also have their own proposal machinery and there are agreements in place to coordinate their operations with the VLBI networks. For instance, an observer that would like to include ALMA as part of an observation with the GMVA needs to send the proposal to both facilities using different proposal tools by different deadlines, for a certain joint observing period that each facility has previously agreed. The TAC assessment process is performed independently, and proposals need to be concurrently approved to be accepted as a VLBI project.

Accepted projects are active for a certain period of time to allow for proper scheduling. In the event that they could not be scheduled within that time frame, observers would need to re-submit their proposals. Most networks define the same active periods but starting at different dates, as their observing cycles do not coincide. Therefore, VLBI observing with several networks simultaneously can only occur during the coincident periods.

Apart from the VLBA and the VLA, who dynamically schedule VLBI observations, the other VLBI networks, as they are composed of different observatories with independent observing programmes, need to schedule their VLBI observations on fixed dates. The same happens, for example, when ALMA participates in GMVA observations.

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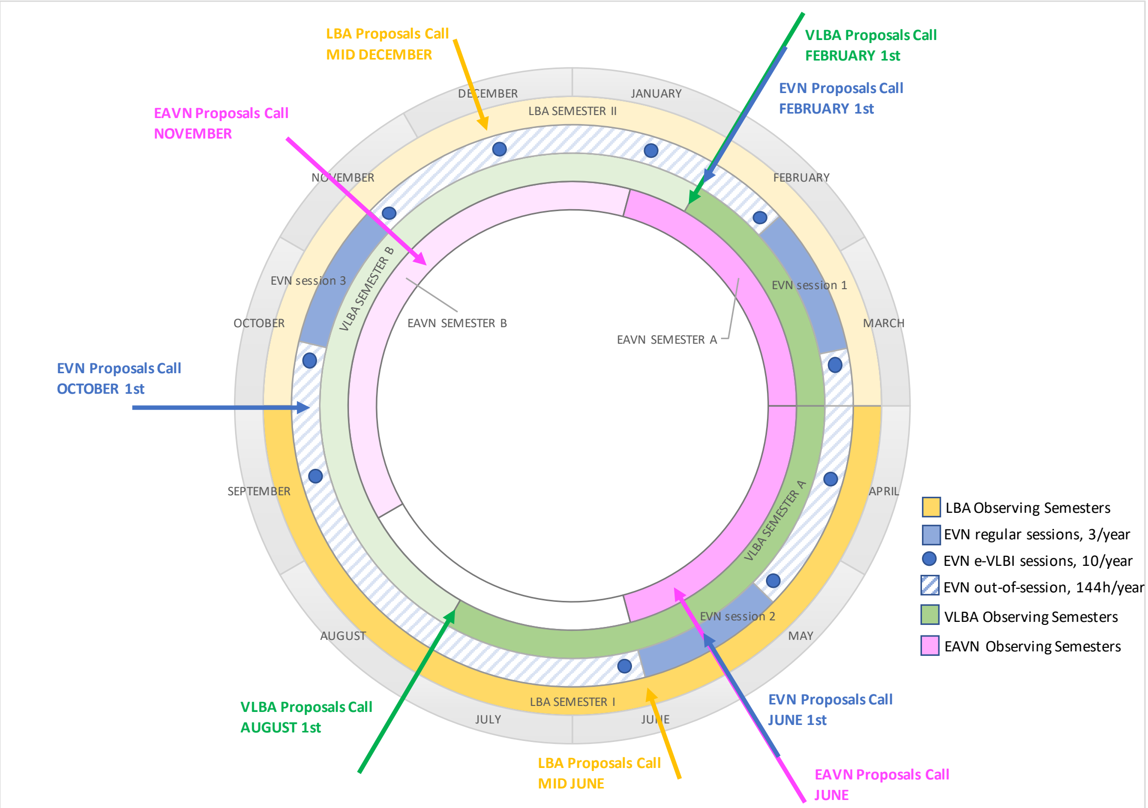

Figure 2. VLBI networks observing cycles and call for proposal deadlines. The rings represent the observing cycles for each network and the arrows the deadlines for the different calls of proposals. The EVN offers different types of observing possibilities: a priori coordinated 3 observing sessions per year (3-4 weeks each), 10 e-VLBI sessions per year (represented by blue dots, 24h each) and possibility for 10 out-of-session observations (up to 144h/year). Dates of the different events for all the networks are approximate and may change slightly from one cycle to the following.

Proprietary periods range between 12 to 18 months, generally starting from the data released date. For ToO projects, the proprietary periods are usually reduced to 6 months, and networks may impose additional constraints for Principal Investigators (PIs) to retain their proprietary rights, as it is the case for the LBA network.

For science operations (Table 2), the VLBI networks offer continuum and spectral line observing modes, in single or dual polarisation, with the possibility of more complicated modes for pulsar observations, larger fields of view with different phase centres, etc. There are different solutions to transfer the data from the individual antennas to the various correlator centres. In the past, data was recorded to custom made hard-disk packs which were shipped after the observations. A global disk pool was established which is still partly in use - this allowed fluent collaboration between certain telescope networks and correlators, such as the EVN and VLBA. Initially the choice of correlator was established in the operational model, based on the observing modes and the distribution of the proposers. For

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global observations, the current default correlator is JIVE. Today, the preferred way to send data is by e-transfer for all types of observations, even if the correlation itself is not real-time. This simplifies the procedures but requires that observatories purchase the necessary equipment and storage capacity (FlexBuffs) for both the telescope and the correlator on the other side of the data transfer.

The observers use the NRAO *SCHED* program to prepare the observing schedules. The main output of *SCHED* is the VLBI EXperiment Definition (VEX) file that specifies all details of the observations from the frequency setup to source positions. This was first defined within the geodetic VLBI community in 1995, but then became widely used as a global standard in astronomical VLBI as well. At the EVN the *pySCHED* program (developed in JUMPING JIVE WP8 “Global VLBI Interfaces”) has been recently introduced. It includes a broad range of the latest VLBI backends implemented and advanced plotting functions. This application is particularly well suited for global VLBI observations. The VEX standard has been adopted by all the VLBI networks. At the observatories, the Field System *drudg* application is used to generate telescope specific schedule and procedure files. In the case of the VLBA they regenerate the schedule from the original user inputs instead of applying the VEX file prepared by the user. This allows dynamic scheduling of the experiments. The VLA has a custom application to generate their schedule OPT files from the VEX files. At the correlators, the observed VEX files are updated with the latest Earth Orientation Parameters (EOPs) and station clock parameters, and then use this VEX file for data correlation. Introducing new observing modes (e.g. using multiple beams) will require adjustments to the VEX standards. Currently the definition of the VEX2 standard is in progress.

Each VLBI network has rules on when observers need to provide VEX files and how they should prepare them properly, including scans on calibrators for different purposes: fringe finding, bandpass calibration, phase and amplitude calibration, pointing, etc. The connected interferometers, including the ATCA as part of the LBA, also impose restrictions for phasing-up the array. Examples of these limitations are the maximum array baseline to be phased-up, minimum flux densities for the compact sources used as calibrators and the need to include scans for re-phasing during the observations. The re-phasing cadence depends on the observing frequency and the array configuration, weather conditions, etc.

The different observatories that participate in a VLBI network need to join operations and technical groups for coordination of the observations and nominate representatives in the group, such as the technical friend and the VLBI friend. These representatives make sure that the telescope is capable of carrying out the observations and is well calibrated, to provide useful science. The single dish calibration parameters must be regularly provided to the network. Some of these are measured before the observations (gain curves, primary beams, noise diode versus frequency), while others are recorded during the observations (system temperatures, GPS vs. data formatter time difference, antenna off-source times). All these metadata conform to certain format standards and are provided to the correlator centres by different means, such as using a wiki page, e-mail, or SFTP to a server for example.

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Additionally, the connected interferometers are able to simultaneously provide, with the VLBI data, their local interferometer products (visibilities, secondary calibrator flux densities and polarization position angle information, as well as images) to improve the calibration of the VLBI observations. This is particularly important for VLBI because all primary flux calibrators are resolved on long baselines, therefore the flux scale is usually uncertain by 10-20%. The VLA also offers simultaneous P-band observations and Fast Radio Bursts (FRB) searches while the array is observing. Some of the single dish observatories have some commensal functionality as well, for example simultaneous VLBI and pulsar backend observations have been made possible in Arecibo and Effelsberg for fast transient searches. Commensal observing will be a cornerstone of SKA-VLBI.

Nowadays the VLBI correlation process is quite standard, in data products and format. Most networks use software correlators, with compatible outputs. But the inclusion of multi-beam instruments and new observing modes will increase the processing load on the VLBI correlators by more than an order of magnitude. In addition, VLBI processing centres will have to find a solution to handle larger amounts of data and data rates arriving at the correlator, due to the wider observing bandwidths and multi-beam instruments. The Global VLBI Alliance will work on further standardizing VLBI processing and data products.

Some of the VLBI networks require the proposing team to participate in the observations. For example, at the LBA network, a trained member of the proposing team is required to monitor the on-going observations. Usually, the VLBI observer is responsible for calibration, imaging and analysis of the data with certain levels of support provided by the networks (e.g. the EVN provides an automatic pipeline to help with data post-processing).

Table 1. VLBI networks operational models: Access to data and resources

VLBI Network	Access	Proposals Types	Proposals tool and deadlines	Projects active period	Observing Cycles	Scheduling	Proprietary period
LBA	Open sky but limited number of VLBI sessions (plus ATCA & Parkes private projects) Scientific merit and technical feasibility	Standard; Time critical (ToO and triggered NAPA); Director's time	ATNF OPAL Mid-Dec & Mid-June ToO (and Director's) any time by e-mail to ATNF Alert group	1 year	2 semesters: (21 days/yr) I=Apr/end-Sep II=Oct/end-Mar	Fixed dates For ToO and NAPA no fast response Time lost due to overrides or failures to be replaced	18 months ToO additional rules: publish results 1 week after observation to retain data rights Approved proposals coversheet and targets list made public

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VLBI Network	Access	Proposals Types	Proposals tool and deadlines	Projects active period	Observing Cycles	Scheduling	Proprietary period
EVN	Open sky Scientific merit and technical feasibility	Regular (disk, e-VLBI, trigger, out-of-session & globals); ToO; Short observations Joint observations for global VLBI	EVN NorthStar February, June & October ToO & short (and manual triggers) any time by e-mail to PC chair	1 year (9m automatically triggered e-VLBI projects)	3 observing sessions (3-4 weeks each) 10 e-VLBI sessions (24h each) 10 out-of-session (144h/yr)	Fixed dates Dynamic for automatically triggered e-VLBI, 10min response	1 year from data release ToO 6 months
EAVN	Open-use on share-risk basis Scientific merit and technical feasibility	Regular, Large Projects, ToO (trigger and DDT)	EAVN website in latex format June & November	1 year for triggers	2 semesters: (500h/yr) A=mid-Jan / mid-Jun B=Sep/mid-Jan	Fixed dates	18 months from data release Raw data deleted 1 month after correlation
VLBA	50% open sky Scientific merit and technical feasibility GBT time and VLA time very limited, well justified.	Regular; Large; Triggered; Directors' Discretionary Time (DDT, 5% of total) for a ToO or Exploratory Time Joint programmes with XMM, Chandra, FERMI, Swift and HST	NRAO PST or EVN NorthStar for VLBI Global February & August DDT any time using PST	1 year	2 semesters: A=Feb/end-Jul B=Aug/end-Jan	Dynamic Fixed dates for Global VLBI	1 year from last observation ToO 6 months
VLA as VLBI element	Open sky, high pressure Scientific merit and technical feasibility	Regular; Large; Triggered; Directors' Discretionary Time (DDT) for a ToO or Exploratory Time	NRAO PST or EVN NorthStar for VLBI Global February & August DDT any time	1 year	2 semesters: A=Feb/end-Jul B=Aug/end-Jan	Dynamic Fixed dates for global VLBI	1 year from last observation ToO 6 months
ALMA as VLBI element	Open sky but 5% time cap for VLBI Scientific merit and technical feasibility	Specific VLBI proposals (only continuum in Band 3 and 6) No time critical projects	ALMA OT and NRAO PST for GMVA Mid-April	1 cycle	11 months cycle (Oct-end Aug) 2 weeks for VLBI (Spring & Autumn)	Campaign mode with fixed dates	1 year from data release
SKA as VLBI multi-element	Member quotas (PI and KSPs) & 5% open sky VLBI observing mode available	Standard (PI); Key Science Project (KSP); Open time (OT); Director-General Discretionary Time (DDT)	SKA Proposal Handling Tool Call for Proposals TBD	TBD	TBD	Dynamic Fixed dates for VLBI	1 year assumption for PI programs For KSP programs TBD ToO TBD

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VLBI Network	Access	Proposals Types	Proposals tool and deadlines	Projects active period	Observing Cycles	Scheduling	Proprietary period
	for all projects Scientific merit and technical feasibility						

Table 2. VLBI networks operational models: Science operations technical information

VLBI Network	Observing modes	Recording modes	Schedules	Phasing	Calibration	Correlation	Support
LBA	Standard continuum 256 Mbps (up to 1 Gbps and spectral line need ATNF support)	Disk-based with shipping and e-transfer e-VLBI (not all LBA stations)	VEX using NRAO sched PI to provide 2weeks before month of observing date. Include fringe finders, phase calibrators, ATCA re-phasing scans, ATCA flux calibration scans.	For ATCA phasing include re-phasing scans	ATCA hybrid mode: VLBI data plus local interferometry data (include ATCA flux calibration scans) Wiki page for each project to include metadata from participating antennas	DiFX @ Pawsey SCC Support from PI not needed	PI to monitor observation progress locally or in remote PI responsible for Calibration, Imaging and Analysis, support from ATNF
EVN	Standard 2 Gbps (or mixed mode observation) Different frequency bands, frequency agility Different observing modes: continuum, spectral line, pulsar gating/binning, polarisation, phase-referencing, large FoV Future commensal observing	Disk-based with shipping and e-transfer (stations to follow disk pack shipment rules and invest 7000€/year) e-VLBI (stations to follow e-VLBI recommendations)	VEX using NRAO SCHED or JIVE pySCHED	N/A	Continuous calibration and ON/OFF High frequency observations to include pointing checks Stations to: - keep technical and calibration info up to date - Provide logs, feedback and calibration files for each experiment - Provide GPS data daily - Check EVN pipeline results	EVN s/w correlator @ JIVE (SFXC) Global VLBI are correlated by EVN	Stations to join EVN TOG group and meetings and subscribe to EVNtech JIVE support for all observing phases, EVN pipeline Each station to invest on EVN spare parts 3000€

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VLBI Network	Observing modes	Recording modes	Schedules	Phasing	Calibration	Correlation	Support
EAVN	Subarrays Dual-beam only for VERA 1 Gbps, one pol (LHCP), up to 32 MHz channels	Disk-based with shipping and e-transfer.	VEX files	N/A	Hot load chopper wheel for most antennas Continuum or maser sources as various calibrators	Korean-Japan Joint VLBI FPGA based correlator @ Daejeon (KJJVC), integration times and number of channels limited by h/w	EAVN support for all observing phases
VLBA	Standard 4 Gbps (exc. Arecibo and VLA) RDBE digital backend	Disk-based with shipping and e-transfer.	SCHED input .key files by e-mail	N/A	Continuous calibration	Socorro DiFX correlator Additional correlator resources (e.g. multiple phase centres) to be supported by observers	NRAO support to new or novice users
VLA as VLBI element	Standard 2 Gbps (256 MHz per pol) Commensal observing (P-band and FRB searches)	Disk-based, no shipping or e-transfer (Mark5C)	VEX converted to OPT using vex2opt	For VLA phasing include phasing scans with certain restrictions on compact calibrator flux, cadence, subbands setup and phasing transfer	Continuous calibration, include scan on VLA primary calibrator No pulse calibration, include scan on strong and compact calibrator For >15GHz include pointing scans VLA and VLBA operators to send logs by e-mail	Socorro DiFX correlator	NRAO support to new or novice users
ALMA as VLBI element	Continuum in Band 3 and 6, 4 Gpbs, dual pol	Disk-based with shipping	VEX using NRAO SCHED by MPIfR A cap of 5% for VLBI in total, sessions < 1 week, multi-epoch observations within a week	For ALMA passive and direct phasing restrictions on calibrator and target fluxes, and array maximum baseline	For linear to circular polarisation conversion need to observe targets at least 3h. 25% ALMA overhead	Bonn DiFX correlator	VLBI campaigns supported by experts from VLBI networks
SKA as VLBI multi-element	Multiple VLBI beams per subarray Up to 5 GHz b/w for 2 VLBI beams, dual pol, per subarray Different	Disk-based with e-transfer e-VLBI (stations to follow e-VLBI recommendations)	VEX converted to SKA SB using appropriate custom script	SKA beamforming restrictions to be determined during Commissioning	Only for MID: Continuous calibration and ON/OFF SKA VLBI data plus local interferometry data (include SKA flux calibration	Different correlation centres around the world, possibly but not necessarily collocated with SRCs Capability for correlation	SKA friend of project Support from participating VLBI networks

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VLBI Network	Observing modes	Recording modes	Schedules	Phasing	Calibration	Correlation	Support
	observing modes and Commensal observing within and among subarrays, limited by resources				scans) SKA linear to circular polarisation conversion with similar restrictions as ALMA, to be determined during Commissioning SKA project container with logs, tickets, calibration data, etc.	single- and multi-beam instruments	

3.2 Global VLBI coordinated observations

Giroletti et al. 2011 [RD06] demonstrated real-time e-VLBI observations ever carried out with a global array including radio telescopes in Europe, East Asia, and Australia, reaching a maximum baseline length of 12,458 km. The observations were part of a large multiwavelength campaign in 2009 to celebrate the International Year of Astronomy. Global VLBI observations (where telescopes from various networks participate) have been carried out before, but the requirement of real-time data transfer across continents and instantaneous correlation added another dimension to the problem. It is thanks to the global effort of developing real-time e-VLBI, under the auspices of the EC-supported EXPReS project led by JIVE, that made such a challenging experiment possible. Following are some examples and details on how the different VLBI networks coordinate their observations today, regardless of their different observing cycles and call for proposals dates (as noted in Figure 2), TAC processes and policies.

The LBA and the EVN networks have agreements to schedule some LBA time at the same time as the EVN sessions, opening the possibility for joint LBA/EVN observations. The easternmost stations of the EVN are at a similar longitude range to the LBA telescopes, and for sources in equatorial regions, baselines to western European stations are also achievable. Proposals for joint LBA/EVN observations need to be submitted separately to both the LBA and EVN for their respective deadlines. If both networks approve the proposal, the schedulers negotiate the observing date.

There is an MoU between the VLBA and the EVN that was renewed in 2000. Proposals for global centimetre VLBI using both networks should be submitted through the EVN NorthStar proposal tool. Global proposals are forwarded to the NRAO and the GBO Time Allocation

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Committees (TAC) automatically, without need to submit them separately. Although proposal deadlines do not coincide, NRAO TAC reviews and grades the global proposals in time for the EVN Programme Committee (PC) meeting. A representative from the VLBA joins the PC meeting whenever global projects are being discussed and grades from both TACs are shared and averaged. If the VLBA does not approve the proposal due to technical or scientific reasons but the EVN does, the observation is performed only with the EVN if the project is still viable.

Selected e-MERLIN antennas were already part of the regular EVN observations, but it is now possible to include the whole e-MERLIN interferometer in EVN observations to provide uv-coverage at short spacings. For these observations, the proposal needs to be sent to both networks and the e-MERLIN's TAC communicates whether or not the proposal has been accepted, without grading it.

The NASA Deep Space Network (DSN), with 3 tracking centres around the world, can also join EVN, LBA and global observations, on a best effort basis, whenever their antennas are free from spacecraft tracking commitments. The NASA antennas participation is very valuable because of their increased sensitivity due to their large diameters. The DSN tracking schedules are decided much earlier than the VLBI schedules, therefore the chance of participation is low, although some antenna time is reserved in advance and there is some room to negotiate schedule changes with the space projects. The Madrid and California DSN sites rely on the EVN and VLBA TACs' decisions, respectively. The Australia site relies on the ATNF TAC. The DSN Madrid site participates in the EVN technical and operations group, providing a technical and VLBI friend. Currently the Jet Propulsion Laboratory (JPL), who is responsible for the operation and maintenance of the DSN, is an associated member of the EVN.

Individual telescopes from a VLBI network may also participate in the observations with other VLBI networks. That is the case for telescopes from the Korean VLBI Network (KVN), the EAVN, or the Russian QUASAR network that participate in EVN observations. All of them are members or associated members of the EVN and therefore, they follow the EVN operational model. An analogous situation occurs with the LBA network, where for example the HartRAO radio telescope operates with the LBA and is also a member of the EVN.

Many radio telescopes around the world also participate in the observations of the International VLBI Service for Geodesy and Astrometry (IVS). This has to be taken into account when scheduling astronomical and geodetic/astrometric projects.

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3.3 VLBI in multi-frequency and multi-messenger observations

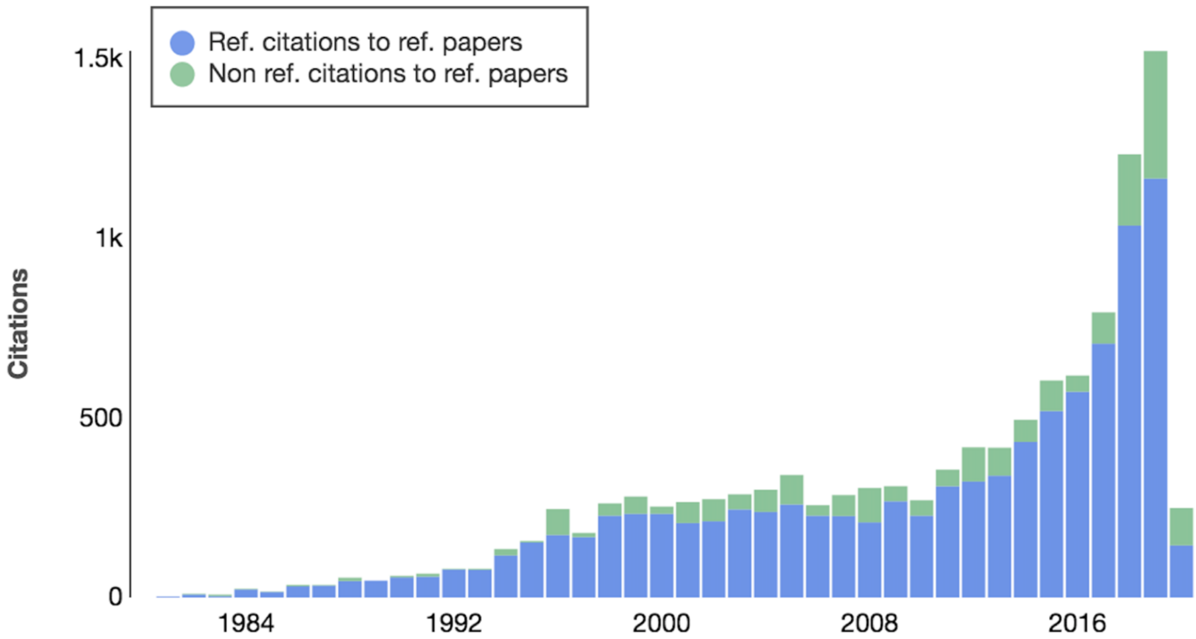

Figure 3. Top 100 EVN papers citation history. The figure shows the number of citations EVN/global-VLBI papers receive each year. The increase after the mid-90's is attributed to the MkIV upgrade of the network as well as the beginning of MkIV correlation and the EVN Archive at JIVE. After 2010, there was another increase, likely due to the impact of the maturing real-time e-VLBI operations, moving to the EVN software correlator (SFXC), and a continuous expansion of the array. The recent sharp peak is clearly related to the new science that marks the beginning of the multi-messenger era, including FRBs and GW-EM counterparts, plus the long-term impact of stellar maser work (figure extracted from JUMPING JIVE deliverable "VLBI20-30: a scientific roadmap for the next decade. The future of the European VLBI Network", RD18).

Multi-wavelength and multi-messenger joint programs have plenty of benefits. These programs result in an increase of the number of proposals, as the facilities become easily available to scientists without previous expertise in the various observing techniques. The impact and quality of the science also greatly improves. As an example, Figure 3 shows the number of citations EVN/global-VLBI papers receive each year, with a sharp recent increase due to new science, such as FRBs and GW-EM counterparts. Figure 4 shows the XMM-Newton publication trend in high impact journals, with almost an order of magnitude increase since joint programs started, with 20% of total proposals falling within this category.

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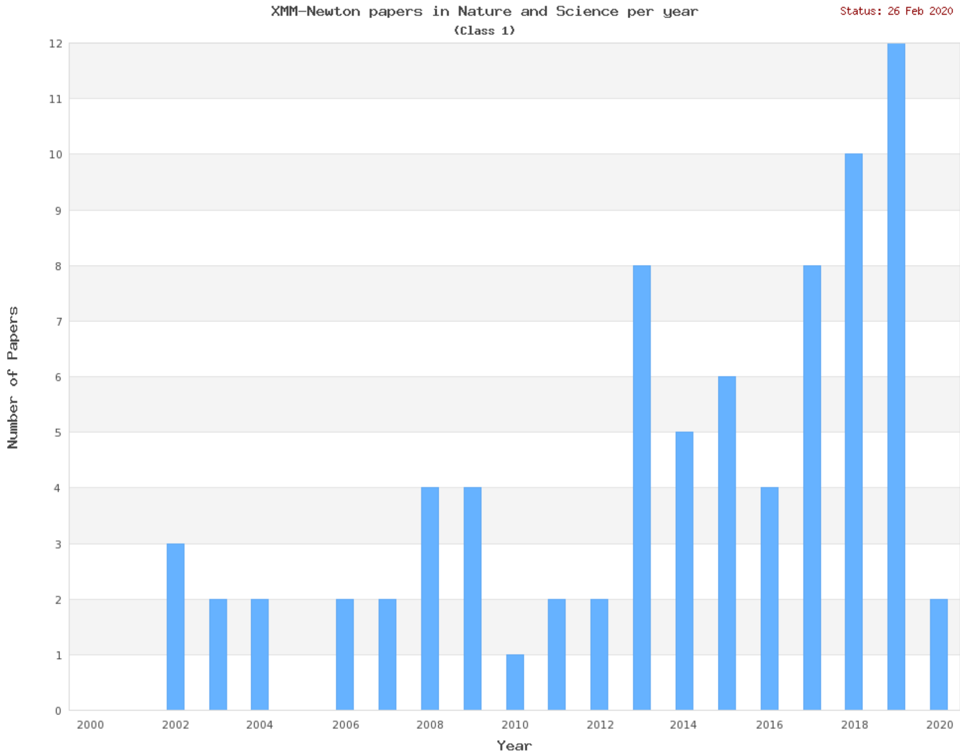

Figure 4. XMM-Newton number of publications in high profile journals. Since joint programs for multi-wavelength and multi-messenger science started and the number of ToO programs increased in the XMM-Newton project, the number of papers in Nature and Science have increased almost an order of magnitude. Source: XMM-Newton website (https://www.cosmos.esa.int/web/xmm-newton/refereed-publications)

A multi-wavelength program worth mentioning is the agreement between the XMM-Newton telescope and NRAO for joint X-ray and radio observations (Annex 1.6, RD10). For this collaboration, the observers just need to send the observing proposal to one of the facilities, and that facility is able to assign up to an agreed amount of observing time on the other facility. The joint observations do not have to be simultaneous, but in case they need to be, fast response to triggering is not guaranteed. Similar agreements are being envisioned for scientific collaboration between the future observatories, such as the CTA and the SKA observatories.

For the particular case of multi-messenger observations, VLBI provides the most precise sky localisation of the radio counterpart for gravitational wave events, down to milliarcsecond spatial accuracy. To fully exploit this capability the Euro VLBI Transient Follow-up Group (Euro VLBI), a group formed by collaborators from the EVN network, signed a Memorandum of Understanding with the LIGO/Virgo Consortium defining policies on data and information sharing. This led to VLBI detection of the afterglow of the binary neutron star merger that produced the gravitational wave event GW170817 (Ghirlanda et al. 2019, RD19). From the

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latest O3 LIGO/Virgo observing cycle (April 2019- April 2020) the alerts are made public as notices and circulars distributed through the Gamma-ray Coordinates Network/ Transient Astronomy Network (GCN/TAN) System and no further agreements are needed.

Discussions at the recent ESA/ESO Science Operations workshop, devoted to cross facility collaboration in the multi-messenger era (November 2019, https://www.cosmos.esa.int/web/sciops-2019), showed that the different multi-messenger facilities, in general, do not support the establishment of a super TAC to handle joint collaborations, although repeatedly prompted by the scientists. As the number of transient alerts steadily increase and telescopes such as LSST, ELT and the new generation of gravitational wave detectors have the potential to surpass current observing capacities, automatic ways for communicating the alerts (e.g. through VOEvents), dynamic scheduling and automatic pipelines are encouraged. Different prototypes for these systems are currently being developed. It has to be noted that automated alerts can only be implemented for dedicated VLBI networks (or their subarrays), because global VLBI observations require coordinating observations well in advance.

3.4 VLBI Operational Model constraints for SKA-VLBI

After studying the different VLBI networks operational models and how they collaborate with each other and other multi-frequency and multi-messenger facilities, the following list of constraints have been identified for consideration for the SKA-VLBI operational model:

- VLBI networks are open sky facilities, available to all observers, with access based on the scientific merit and technical feasibility of proposals.
- Each VLBI network has different observing cycle definitions, with different dates. Some networks, such as the EVN network, also offer possibilities for Out of Session observations.
- VLBI networks offer a limited amount of observing time per observing cycle due to the various limitations to what the networks can offer or due to already committed time. They do not impose time caps.
- Each VLBI network uses different proposal handling systems, proposal calls with different deadlines and different TACs and policies. For global or joint observations, there are different agreements in place to facilitate the collaboration and overcome these differences, but the solutions are broad and varied. All these differences will need to be taken into account when joining their individual or joint observations.
- In general, VLBI networks accept regular proposals and time critical proposals. Time critical proposals are either triggered or Target of Opportunity (ToO) proposals.
- VLBI networks accept ToO proposals any time, usually by e-mail.

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- VLBI networks' response to critical events is typically of the order of several days. There is no fully automated response to triggers, either generated internally or externally.
- VLBI observations need fixed scheduling for proper coordination of the different radio telescopes and facilities that participate in the observations. The only network that uses dynamic scheduling for its own VLBI observations is the VLBA.
- VLBI networks have similar project lifetimes but as their observing cycles do not coincide, agreements are needed to define common observing periods for joint observations.
- Unless prescribed by safety procedures, VLBI observations are not usually stopped or cancelled due to weather, RFI or similar uncontrolled problems. In the case of technical problems that ruin the project success, the observation may be repeated. Scheduling coordination for the next observing cycle is required to give time back to VLBI projects. VLBI observing time cannot usually be added from different observing dates, the whole observation will have to be repeated, with the same total observing time, as originally planned.
- VLBI networks have similar proprietary periods counting from the data release date or the date of the last observation included in the project. For most networks, the proprietary period is 12 months, with the exception of the LBA and the EAVN with up to 18 months. Proprietary periods for ToO projects are usually reduced to 6 months. The LBA network imposes additional rules to ToO projects to guarantee data rights.
- VLBI science operations are extremely complex due to the use of different antennas, receivers, VLBI backends, etc. Effort must be taken to keep these standardized as much as possible, to allow for collaboration between the various networks and facilities. Stakeholders must ensure compatibility of observing modes, use of standard data formats (e.g. VDIF standard), availability of scheduling tools compatible with all instruments, common calibration processes, and calibration information recorded in the form of standardized logs and metadata files. At the time of writing, a Global VLBI Alliance is envisioned to foster a global collaboration for VLBI, to prepare the networks including the SKA, for present and future challenges.
- Individual observatories participating in the observations of a VLBI network need to be involved in the operations and technical groups of the network.
- Phased-up interferometers impose additional restrictions on the design of VLBI observations. If required, they provide additional data products (local interferometer data and calibration data).
- VLBI observations are not multiplexed (i.e. commensal observing), but some of the array elements (single dish or connected interferometers) have started piggy-backing other projects while performing VLBI, such as fast radio transient searches.
- The VLBI correlation process is quite standard, with standard data products format. Most networks nowadays use software correlators, with compatible outputs. Multi-

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beam instruments and broader observing bandwidths will increase the correlator processing load and complicate the data handling.
- VLBI observations are either correlated in real-time (e-VLBI observations) or after the observation has been performed and data has been transferred to the VLBI correlators (standard observing). Not all networks have full e-VLBI capability.
- The PI is responsible for the calibration, imaging and analysis of observations from current VLBI networks. Usually the networks support the PI through the different phases of the project. In the case of the EVN, expert user support is provided by JIVE.
- There are agreements between astronomical facilities operating at different wavelengths for joint multi-frequency observing programs. Some of these agreements allow facilities to assign a percentage of observing time on the other facility. Joint observations can be simultaneous or not, but no fast response to triggers is offered for simultaneous observations.
- The different multi-messenger facilities, in general, do not support the establishment of a super TAC to handle the joint collaboration.
- As the number of multi-messenger alerts steadily increases, automatic ways for communicating the alerts (e.g. VOEvents), dynamic scheduling and automatic pipelines are encouraged.

4 SKA1 Operations Plan

The Operations Plan for Phase 1 of the SKA Observatory [RD03] defines:

a) how the SKA Observatory will be operated, including (and emphasising) the operation of its two telescopes; and

b) the required resources to implement the plan.

The final version of the SKA1 Operations Plan will be submitted to the Council of the SKA Observatory at the same time as the SKA1 Construction Proposal.

The following sections briefly outline the SKA1 Operations Plan and the constraints that will need to be considered in formulating the SKA-VLBI Operational Model. Annex 2 offers a complete discussion of the SKA1 Operations Plan, section by section, outlining the aspects that apply to the SKA-VLBI capability and to the VLBI networks. Sections that do not apply to the present study have been omitted.

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4.1 SKA1 Operational Model

The SKA Observatory will comprise two radio telescopes of very different nature, that will be built in South Africa and Australia, with the Global Headquarters located in the United Kingdom. The scope of the project is about two orders of magnitude larger than current radio astronomy observatories; therefore, completion has been planned in two phases, SKA Phase 1 with a modest initial deployment but enough to surpass current observing capabilities, and SKA Phase 2 at the full scale.

The SKA1 project design responsibility was distributed to different Consortia from the member countries, with the SKA Organisation as the technical design authority. The Baseline Design [RD04] of the SKA1 has already successfully passed the Critical Design Review in preparation for the Construction Phase.

The SKA1 Operations Plan [RD03] is constrained by the distributed nature of the organisation, and other aspects such as the Hosting Agreements, the Convention, Health, Safety and Environmental policies, radio quiet zones establishment and maintenance, and interface with the SKA Regional Centres. The SKA1 Operations Plan is primarily based on the principle of its operation as a single, centrally managed, observatory. It also puts emphasis on the remoteness of the telescope sites, automated and remote operations, high operational availability with 24h operations, a flexible observing programme, multiplexing of the different science programs and delivery of science-ready data products to the users.

The different types of multiplexed or commensal observing contemplated by the SKA Observatory are:

- Data Commensality: multiple projects can use the same Observatory Data Products but for different science goals;
- Observing Commensality: multiple projects can use the same field of the sky and telescope/instrument configuration, but they each need different observatory data products;
- Multiplexed Commensality: the ability to use multiple subarrays and/or tied-array beams for different projects to concurrently observe different fields of the sky.

The SKA Observatory will accommodate a mix of large coordinated observations proposed by large teams (i.e. Key Science Projects) and PI-driven programmes, both only for scientists from member countries. A small percentage of time will be available for scientists from all countries (Open Time), including the member nations. The SKA Access Policy (to be approved by the SKA Council) will describe the access rights for observing time and science data products. Details of the implementation of this Access Policy will be described in the SKA Access Rules and Regulations document, including details of SKA observing cycles, proposal deadlines, TAC processes, proprietary periods, etc. The cadence of KSP proposals may be different to PI proposals, as well as their policies.

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To support the operations of the SKA Observatory, each Host Country will provide a Science Operation Centre (SOC), an Engineering Operations Centre (EOC) and a Science Processing Centre (SPC), for operation, maintenance and data processing and long-term archiving functions. A network of SKA Regional Centres (SRCs) - outside the scope of the SKA construction project - will provide users with access to the SKA science data products (as well as the processing capacity necessary for further processing and analysis of those data products) and will give support to the local astronomical communities. The SKA Observatory will also support a Development Programme to enhance and include new capabilities over its lifetime.

4.2 Operational constraints for SKA-VLBI

After studying the SKA Operations Plan [RD03, Annex 2 discussion], some constraints are identified for consideration in the development of an SKA-VLBI operational model:

- Previous versions of the SKA Operations Plan assumed that a Global VLBI Consortium would be established. The present document makes the distinction between a Global VLBI Alliance to support VLBI activities worldwide and a SKA-VLBI Consortium, not necessarily global, that will exclusively support the SKA-VLBI capability.
- The SKA development programme will be applicable to the VLBI capability as one of the observing modes of the SKA Observatory. SKA-VLBI development may need to be coordinated with the SKA-VLBI Consortium, for compatibility. SKA may use this opportunity to enhance the VLBI capability (e.g. more beams, more bandwidth, etc.).
- The VLBI equipment (software and hardware) for the SKA telescopes is not included in the SKA Construction budget. It is assumed that the SKA-VLBI Consortium will develop and provide the VLBI equipment for the SKA Observatory. On the contrary, the SKA budget covers the implementation of the VLBI mode in the correlator-beamformers and the transport of the VLBI data from the telescopes sites to the Science Processing Centres (SPC), where the VLBI backends for each telescope will be installed. The SKA project also covers the implementation of the real-time beamforming calibration at the Science Data Processors (SDP).
- The SKA VLBI design is described in the SKA System Design Baseline document [RD04], following its definition provided by the JUMPING JIVE project [RD01]. The VLBI design is based on modular line replaceable units (LRUs), uses SKA Tango for monitor and control functions and has taken into account SKA standards and recommendations.
- The VLBI equipment provided by the SKA-VLBI Consortium will be installed at the SPCs, in Perth and Cape Town. The SKA-VLBI Consortium may acquire additional commitments for support of the VLBI equipment.

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- From the SKA Engineering Operations point of view, the VLBI equipment could be considered part of the SKA equipment (although provided by a different budget source). Therefore, it will be subject to SKA configuration control rules, and will need to be included in the PBS with appropriate spares provided by the SKA-VLBI Consortium.
- SKA project types include: PI and KSP (for members), Director's Discretionary Time (DDT), and Open Time (for members and non-members). As a standard observing mode for the SKA, VLBI will be available for all types of SKA projects.
- It is expected that the VLBI equipment provided by the SKA-VLBI Consortium will be made available for all SKA projects requesting the VLBI observing mode, and will not depend on the participant VLBI networks being part of the Consortium, always subject to VLBI buffer availability.
- SKA access will be proportional to member shares in the SKA project, but a small amount (Open Time) will be accessible to all users.
- VLBI proposals fall within the category of SKA coordinated proposals.
- Proposals requesting the VLBI capability should include VOEvents rules if they trigger events during their observation (internal or external to SKA).
- The SKA proposal review process will be based on scientific merit and technical feasibility. A process for VLBI proposal evaluation with SKA participation will have to be agreed.
- The SKA TAC may wish to recommend override status to projects with highest priorities that will immediately abort, or stop at the end of the scan, the on-going observations. In the event of cancelling VLBI projects where SKA participation is essential for the success of the project, the VLBI observations may need to be repeated.
- Observatory data products are the property of the SKAO. In the particular case of SKA VLBI data, once VLBI correlation is completed, it will be deleted from the SKA VLBI equipment and from the designated VLBI correlator buffer, to free the buffer for future observations. This is the usual procedure followed for data from the VLBI antennas.
- It is currently assumed that SKA science data products will have a proprietary period of 1 year (to be approved by the SKA Council). Although equivalent to most VLBI proprietary periods, some synchronisation for VLBI projects may be necessary. SKA may need to define proprietary periods for ToO projects.
- The SKA's flexible observing programme should allow VLBI projects to be accommodated even when they are scheduled close to the observing dates. SKA will need to make sure that higher priority projects than the VLBI projects are also observed during the same observing cycle, as the former may be impacted by scheduling constraints and Quality Assessment (QA) rules, but the VLBI projects will not, as they are not dynamically scheduled.

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- Observation planning for each SKA telescope will be executed considering all known constraints: maintenance and commissioning schedules, simultaneous SKA1 or coordinated observations, target visibility, etc. The SKA VLBI schedule will inform the SKA maintenance and commissioning schedule and vice versa.
- SKA multiplexed programmes may inherit scheduling priorities from each other. SKA-VLBI is compatible with all types of SKA commensality, limited by availability of SKA resources.
- For approved proposals requesting the VLBI observing mode, the SKA Scheduling Block (SB) will be generated using the VLBI VEX file and additional information attached to the project using the Observation Design Tool (e.g. VLBI correlator destination Internet Protocol -IP- address). VLBI projects should include appropriate Quality Assessment (QA) rules as VLBI projects are not usually stopped or aborted due to adverse weather conditions or data quality assessments, unless prescribed by SKA safety procedures. SKA Project containers will include metadata and logs after observation completion, and any ticket opened due to problems encountered.
- In case of problems during an observation, the SKA operator may decide to halt and later continue or repeat the scheduling block (SB) depending on the severity of the problem encountered and will need to submit a ticket describing the fault for future investigation. For SKA-VLBI the SB cannot be repeated and needs to be executed at a fixed time. In the event that a VLBI observation is cancelled due to technical problems, it may need to be repeated at a later coordinated date.
- The relationship between the different VLBI networks with the SKA-VLBI Consortium could be based on MoUs.
- SKA telescopes will be capable of 24-h operation. VLBI observations (real-time correlation or not) need local support from staff at the antennas and the correlator. This will impose constraints on the SKA-VLBI observing dates.
- The SKA Observatory will calibrate SKA data and make science-ready data products and ancillary data products available to the users. The level of compromise of the VLBI networks with their users is different, as VLBI networks do not provide science-ready data products but assist the users with data post-processing.

5 SKA-VLBI science cases operational outcomes

The JUMPING JIVE deliverable D10.3 “Portfolio of SKA-VLBI science cases” [RD02] and Paragi et al. 2014 [RD09] present a broad range of examples of the science that can be realised using the SKA-VLBI capability, with both SKA1-MID and LOW telescopes observing as part of the VLBI networks. The science cases inform the design of the SKA1 Observatory with respect to the capabilities needed, requirements, and may uncover limitations imposed by

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the design. They also inform about the observing strategies and modes, science data products, issues to be determined or solved, etc.

This section briefly reviews the outcomes to emerge from the portfolio of science cases with a focus on operations, i.e. how the SKA will be configured and used to support the SKA-VLBI science, number of subarrays and sizes, number of VLBI beams, observing modes, science data products, and SKA resources needed (including CSP, SDP, SRC and network connection), etc. Following are the identified constraints to be taken into consideration for the SKA-VLBI operational model:

- SKA-VLBI science will be able to equally exploit SKA1-LOW and SKA-MID telescopes. Although the number of possible projects presented for LOW (7 projects) is considerably fewer than for MID (22 projects), the number of observing hours these use cases imply is very similar for both, approximately 32000 hrs. It is understood that only a fraction of this time will be available at the SKA for VLBI observations, still, it demonstrates the strong interest in the community to realize SKA-VLBI. According to the example projects, the pressure for VLBI networks at LOW and MID frequencies will be similar, while it is also clear that currently there are not many telescopes available at low frequencies to carry out VLBI observations.
- Some SKA-VLBI projects need a very reduced VLBI network, e.g. global astrometry or scintillation projects, where just one or few baselines are required.
- For SKA1-MID, approximately half of the projects will be performed using the low frequency bands (mostly Band 2), while the other half will use the high frequency bands (mostly Band 5). From the examples presented, at least 8 projects need dual-band observations, observed either simultaneously (using SKA subarrays or frequency agility) or close in time (similar observing dates). The VLBI networks will need broadband receivers to support dual-band observations, and if not available, definition of different sub-networks for each frequency band (e.g. RadioAstron project co-observing).
- The SKA1-MID Band 5 split impacts all AGN, scintillation and global astrometry projects. At least 4 projects could benefit from a Band 6 extension. VLBI networks will need broadband receivers to support these observations.
- A limited number (two) of SKA-VLBI science projects could benefit from simultaneous SKA1-LOW and MID observations. Therefore, VLBI networks for both frequency ranges should be available at the same time with simultaneous visibility.
- For both SKA1-LOW and MID, about half the science cases request one observing epoch per target (e.g. for surveys), while the other half need several epochs, mostly with a specific observing cadence (e.g. for follow-up studies or parallax signature measurements). This will impose constraints on SKA and VLBI scheduling, VLBI data transfer to the correlators, and SKA and VLBI data products pace production and delivery to the PIs (usually before the next observing epoch).

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- Five projects are time critical and will be either triggered internally or externally to SKA1 or will themselves produce triggers for transients' follow-up. Real-time transfer and correlation (e-VLBI mode) is necessary for four of these projects for fast turnaround of the results. SKA will also need to quickly turnaround the science data products. Additionally, one of the projects (FLARES science case) may need a 1 day or faster response time. This is suitable for the SKA, with dynamic scheduling, but may be challenging for the VLBI networks with response times to critical events of the order of several days. The VLBI networks and the SKA should agree to the use of a common event broker, VOEvent or similar.
- In general, SKA VLBI beams are produced from a core subarray whose size is a trade-off between field of view (FoV) and sensitivity in the beams, and beamforming stability. SKA1-MID, in principle, can beamform up to the whole array (up to 150 km baselines) but LOW is limited to 20 km baselines. Beamforming stability and constraints will be determined during the SKA commissioning activities. Most of the projects will use the 4 km inner core (8 km baselines with 70-80% total sensitivity), but some projects could take advantage of other sizes or selectable size depending on the target. These projects are compatible with the definition of subarray templates for the generation of the VLBI beams. It is important to note that VLBI projects need a stable subarray phase centre, with positions referred to the ITRF and its time referred to the UTC. SKA will need to track position and velocities due to continental drift.
- In some cases, e.g. for dual-band simultaneous observations, SKA VLBI beams will be produced from several core subarrays (up to three), with similar resolution and sensitivity (e.g. SKA and MeerKAT antennas separately). This is also compatible with the definition of subarray templates.
- The number of VLBI beams is limited to 4 by the SKA1 requirements for both SKA1-MID and LOW, although more are allowed by the design. The SKA-VLBI science cases would need more beams for phase referencing techniques and high precision astrometry, and to accommodate a high density of targets within the FoV: up to 8 for LOW, up to 16 -or more- for MID. This will impose constraints on the VLBI correlator, that will have to handle many more elements, with different FoVs and pointings in the sky.
- All studied SKA-VLBI projects need SKA local interferometer imaging (with or without polarisation products) to enhance the calibration of the VLBI results, and/or complement the science return. This is achievable by SKA1-LOW for all cases as all observing modes are provided simultaneously for each subarray, with full bandwidth. For SKA1-MID the same applies for most observing bands but there is a limitation based on correlator resources for Band 5, i.e. the resources provided only allow the full bandwidth of Band 5 to be processed by one observing mode at a time; for more than one observing mode, a bandwidth sacrifice needs to be made.

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- Apart from correlator resources (CSP resources and data transport usage between CSP and SDP), SKA will need to schedule Science Data Processor (SDP) resources, to generate the science observatory data products (ODPs).
- The SKA data products should be accompanied by appropriate metadata (described in detail in the TM-VLBI Interface Control Document [RD05, RD01]), as well as by the SKA observing log and a description of any problems that occurred during the observation, following the standard SKA procedures.
- Apart from SKA local interferometer imaging, some projects would also propose to use other observing modes simultaneously within the same subarray, e.g. spectral line imaging, Pulsar Timing (PST), Transient and Pulsar Search (PSS) and transient search. LOW is able to provide all observing modes simultaneously for each subarray but MID may need to trade-off resources.
- SKA-VLBI data need to be e-transferred to the VLBI correlator either in real-time (e-VLBI mode) or after the observation has been performed. Data will be recorded and transferred using several VDIF recorders, working in parallel. The use of the SKA external network connection will be scheduled. For SKA1-LOW a data rate of 20 Gbps will allow all VLBI science to be performed and data transferred, while for MID data rates will range from 16 to 80 Gbps, with 64 Gbps from a majority of projects.
- SKA-VLBI is compatible with all types of SKA commensal observing, limited by SKA resources. If the suitable resources are available, about 10 projects could be observed commensally with other SKA1 projects, such as the continuum and spectral line surveys, and the global astrometry science cases.

6 SKA-VLBI workshop operational outcomes

The opportunity to prepare SKA Key Science Projects exploiting the SKA-VLBI capability was presented to the scientific community at the 14th EVN Symposium [Paragi et al. 2018, RD08] and culminated with the organisation of the SKA-VLBI Key Science Projects and Operations workshop. The workshop was held at the SKA Organisation Global headquarters, in Jodrell Bank, Manchester, 14-17 October 2019 (https://indico.skatelescope.org/event/539/) and gathered together 65 scientists from 18 different countries, with a large representation of young researchers representing the flourishing VLBI science community. The first part of the workshop was devoted to different aspects of the SKA Observatory, focusing on the SKA-VLBI capability. In the following days, the different talks were organised into sessions of different science topics and presented a wide variety of science that can only be achieved at very high angular resolutions, when SKA1 telescopes are included in VLBI arrays. Discussions of how to realize SKA-VLBI Key Science Projects continued within four working groups. Outcomes from the scientific presentations and parallel discussions will be presented as a JUMPING JIVE deliverable D10.4 "Report on SKA-VLBI Key Science Projects".

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From the SKA-VLBI workshop discussions, the following constraints have been identified to be taken in consideration for the SKA-VLBI operational model:

- The MultiView technique using the SKA-VLBI capability has the potential to improve the relative astrometric accuracy by an order of magnitude compared to that achieved today. For the lower observing frequencies (down from SKA Band 2) a modest increase of the number of VLBI beams will be required, from 4 to at least 6 or 8 VLBI beams.

- Apart from the SKA VLBI beams produced from the phased-up core, individual SKA antennas could be included in the VLBI network to provide short uv-spacings for imaging and calibration, freeing up SKA resources but increasing the data rates that need to be sent to the VLBI correlator.

- Commensal observing is possible for SKA-VLBI, only limited by the availability of SKA resources. VLBI projects can piggy-back other SKA projects, and vice versa.

- It was proposed that VLBI observations with SKA1-MID could be performed every fortnight, following the e-EVN model as an example.

- To complement the VLBI networks at low frequencies, a few additional LOW stations could be installed throughout Australia and nearby countries, following the International LOFAR Telescope (ILT) model.

- The SKA-VLBI workshop science discussions have shown the need to increase the number of VLBI beams provided by SKA, to 8 or 10 sensitive VLBI beams.

7 A model for SKA-VLBI operations

This section is considered a preliminary draft and presents a model for SKA-VLBI operations. The different outcomes and constraints identified in the sections above are discussed, as well as all identified areas that would need discussion and/or agreement. This model will inform the elaboration and future development of the SKA1 Operations Plan.

The SKA-VLBI Operational Model is structured into the following subsections: SKA-VLBI science programmes operational implications, SKA-VLBI operational principles, SKA-VLBI

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operating constraints and a description of the observing configurations and science and engineering operations, with a list of the different assumptions included at the end.

7.1 SKA-VLBI Science Programmes

SKA-VLBI science has the potential to fully exploit the multi-beam capability of both SKA telescopes. The science cases presented in the JUMPING JIVE deliverable “Portfolio of SKA-VLBI science cases” [RD02] show that SKA-VLBI science will be able to equally exploit both SKA1-LOW and SKA1-MID telescopes. Therefore, pressure for VLBI networks working at lower and mid/higher frequencies could be similar, but it will also depend on the available time on the SKA1 telescopes for VLBI science, and the availability of VLBI networks at both frequencies. At MID frequencies, the latter should not be a problem, but there are gaps in the uv-coverage, mostly in Africa. Apart from the International LOFAR Telescope (ILT), the VLBI networks working at LOW frequencies are not as well developed. Both issues will require attention in the mid-term.

There are some outstanding science cases that could benefit from simultaneous SKA1-LOW and SKA1-MID observations. Therefore, VLBI networks for both frequency ranges will occasionally need to be available simultaneously. Other projects will just need a very reduced VLBI network where just one or few baselines would be sufficient.

Another important issue is that many science cases will need broadband observations from mid to higher frequencies. The SKA1-MID offers broadband capability for Band 5 (C-band) but cannot simultaneously observe in lower frequency bands, such as Band 2 (L-band). Different strategies could be followed to support observations across multiple bands, such as using frequency agility, scheduling observations as close as possible, or using different subarrays for each observing frequency. The VLBI networks will also need broadband receivers to support these observations. Receivers that cover at least 14 GHz bandwidth at cm wavelengths are currently in development (BRAND EVN) or are already in use by the VGOS geodetic VLBI network. Optionally, configuration of different VLBI sub-networks for each frequency band could be employed, as was done to support the RadioAstron project.

Most of the SKA-VLBI science projects will be supported using a core subarray that will produce the VLBI beams. The size of the subarray will be pre-defined from a set of templates. The number of VLBI beams is limited to 4 in total by the SKA1 System level requirements, but more beams are allowed by the SKA design. SKA-VLBI science would greatly benefit from using more than 4 beams for high precision astrometric applications and high density of targets within the FoV, with up to 8 beams for LOW and 16 beams, or more, for MID.

Additionally, all projects indicated that they will require simultaneous SKA Imaging. According to the current design, this is possible but only from the same subarray that

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produces the VLBI beams. This may not be ideal for the science goals of some projects, because normally it is only the inner few-km SKA1-MID core that will be phased-up. One of the solutions is to include dishes from the outer regions of the core and/or the spiral-arms in the tied array, but applying zero weights, allowing them to contribute to the imaging but not to the beamforming products. Another alternative for some SKA-VLBI observations may be adding a number of individual SKA antennas or stations as elements in the VLBI array to provide short uv-spacings to the VLBI images. This will release SKA resources as SKA imaging will no longer be necessary and will allow for more commensal opportunities.

Both the increase in the number of VLBI beams and the inclusion of individual SKA elements, not only increases the data volume to be transferred and stored at the VLBI correlator but would also require an enhancement of the correlator compute power.

Half the SKA-VLBI science will be dedicated to surveys with just one observing epoch, while the other half will consist of follow-up studies and parallax signature measurements, with several observing epochs at a particular observing cadence. The latter studies will impose constraints on SKA-VLBI scheduling, VLBI data transfer to the correlators, and SKA and VLBI data products production and delivery to the PIs, usually before the next observing epoch.

Some projects may be time critical, either triggered internally or externally to the SKA, or will themselves produce triggers for transients' follow-up. Real-time transfer and correlation (e-VLBI mode) and prompt VLBI and SKA products delivery will be necessary for fast turnaround of the results. Fast response to critical events may be challenging for the established VLBI networks with typical response times of the order of several days. Future modern VLBI networks should employ dynamic scheduling to easily adapt to the transient astronomical events.

7.2 SKA-VLBI Operational Principles

In this section, operational principles that will guide the SKA-VLBI capability are presented. This preliminary list may be modified by the different stakeholders.

- VLBI is an observing mode of the SKA Phase 1 Observatory.
- As other SKA observing modes, VLBI is available for all types of SKA projects.
- The SKA-VLBI capability is the scientific capability provided when the SKA Phase 1 telescopes are included in VLBI observations.
- An SKA-VLBI Consortium is envisioned as a collaboration between the SKA Observatory and different VLBI networks and observatories, not necessarily global,

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with the purpose to provide support for the SKA-VLBI capability and coordinate the VLBI networks for joint observations with the SKA. This document assumes the existence of such a Consortium, but this will not prevent other agreements between the SKA and the VLBI networks for further collaboration.

- The SKA-VLBI Consortium may not be a legal entity and individual agreements (MoUs) between the SKA Observatory and the different VLBI networks or VLBI observatories would be needed for this joint collaboration.

- The SKA-VLBI Consortium members will develop and provide the VLBI equipment and spares required by the SKA telescopes to enable VLBI observations. The Consortium will support the SKA with the installation and commissioning, science and engineering operations, and decommissioning of this VLBI equipment.

- The Consortium members will also need to equip the VLBI correlators with appropriate buffer and software to support the multi-beam SKA radio telescopes.

- There will be a proposal review process in place to receive and approve SKA-VLBI proposals for observing with the VLBI networks.

- For occasional use, it is expected that the VLBI equipment provided by the SKA-VLBI Consortium will be made available for all SKA projects requesting the VLBI observing mode regardless if the participant VLBI networks and observatories are part of the Consortium, and always subject to VLBI buffer availability. For more regular use, participation in the SKA-VLBI Consortium would be encouraged.

- The SKA Observatory Development Programme (SODP) will be applicable to the VLBI capability as an observing mode of the SKA Observatory. The SKA Observatory may choose to use this programme to enhance its VLBI capability. Coordination with the SKA-VLBI Consortium members will be required to assure compatibility.

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7.3 SKA-VLBI Operating Constraints

In this section, several factors that limit or constrain the SKA-VLBI capability are presented:

- VLBI networks are open sky facilities, available to all observers, while the SKA access will be proportional to members' share in the project, with a small percentage for Open Time (OT), available to all users.
- VLBI observations need fixed scheduling, for the necessary coordination of the different observatories. The SKA dynamic scheduling scheme is advantageous for the inclusion of SKA telescopes in VLBI schedules, usually released close to the observing date. Dynamic scheduling should be considered for certain future VLBI arrays that may be able to accommodate this capability, jointly with SKA.

- SKA-VLBI fixed schedules may impose different constraints on the short-term SKA schedules for maintenance, commissioning, etc. At the same time, SKA schedules (long and short-term) will impose different constraints on the SKA-VLBI fixed schedule.

- The SKA-VLBI capability is compatible with all types of SKA commensal observing, only limited by availability of resources. SKA-VLBI projects may piggy-back on other SKA projects or vice versa. SKA multiplexed programs may inherit scheduling priorities from each other.

- The SKA-VLBI capability needs availability and proper scheduling of different SKA resources: Central Signal Processor (CSP), Science Data Processor (SDP), data transfer, SKA VLBI recording buffer, external data network connection and SKA Regional Centres (SRC) support.

- The SKA-VLBI capability also needs availability and proper scheduling of different radio astronomical facilities and VLBI networks resources: VLBI operational equipment and recording buffer at the participant radio telescopes, NREN data networks usage, correlator processing and correlator recording buffer.

- The SKA1 project construction budget covers the implementation of the VLBI observing mode in the CSP, the transport of the VLBI data from the CPF at the telescopes sites to the SPCs, and the necessary SDP implementation for real-time beamforming calibration and SKA local interferometric complimentary imaging to calibrate the VLBI data products.

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- The SKA-VLBI capability needs adequate and compatible VLBI equipment to be used by the SKA Observatory. The SKA-VLBI equipment and the buffer needed at the VLBI correlators to support the SKA-VLBI capability is not included in the SKA construction budget for the Baseline Design. It is expected that the SKA-VLBI Consortium will be responsible for providing the VLBI Element (including appropriate hardware and software) for the SKA Observatory, for both SKA1-MID and SKA1-LOW telescopes.

- The minimum configuration for SKA-VLBI observations would be just one baseline formed by one phased-up SKA subarray and one radio astronomical facility (one radio telescope, one phased-up interferometer, etc.). Normally, this collaboration will be extended to a fraction or a complete VLBI network, or to several VLBI networks for global observations.

- SKA participation in VLBI observing can be limited to one subarray containing one single MID antenna or LOW station (e.g. for verification, commissioning, debugging of problems, calibration, etc.). Normally SKA participation in VLBI observations will consist of one or several phased-up subarrays containing one or more SKA antennas/stations that produce several VLBI beams, with the maximum number of antennas/stations, subarrays and VLBI beams limited by the available SKA resources.

- The SKA-VLBI equipment will be located at the SPC, in Perth and Cape Town, where the SDP will be hosted. This will allow easy access to this equipment by the SKA-VLBI Consortium.

7.4 SKA-VLBI Observing Configurations

This section details the different observing configurations that will be exercised to support the SKA-VLBI science discussed during the Key Science Projects and Operations workshop.

Typically, the SKA will participate in VLBI observations providing a number of VLBI beams formed from a core subarray. The size of the subarray will be selected depending on the required FoV and sensitivity for the beams. Ultimately the size of the core subarray will be limited by the beamforming stability conditions, but SKA1-MID is capable of beamforming from the whole array while SKA1-LOW is limited to 20 km baselines. The number of VLBI beams and their sensitivity will depend on project requirements, with the possibility to exploit the full capabilities provided by the SKA correlator design, with a maximum of 52 low sensitivity VLBI beams per subarray for SKA1-MID and a total of 16 full bandwidth beams for SKA1-LOW. The VLBI beams can be pointed to different positions on the sky, but within the primary beams of the largest VLBI antennas participating in the observation. How the different beams will be configured and pointed will depend on the observing modes

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employed for the observations such as targeted or survey mode. These different observing modes are fully discussed in the JUMPING JIVE deliverable D10.4 “Report on SKA-VLBI Key Science Projects” [RD19].

Simultaneously to the VLBI beams produced from the core subarray, the SKA-VLBI projects will need SKA local interferometer imaging products for calibration purposes. By default, these imaging products will be provided from the same core subarray that generated the VLBI beams, in single or dual polarisation. For SKA1-MID the VLBI observing mode will provide these products at lower than SKA standard spectral resolution without using additional processing resources. In the case where full spectral SKA resolution imaging products or high-resolution spectral line imaging products are needed, appropriate SKA1-MID correlator resources will need to be allocated, if available. For SKA1-LOW the imaging products will always be provided from the same subarray with full spectral resolution.

Depending on the characteristics of the calibrators, some projects may need SKA simultaneous imaging products produced from the whole SKA array. As the SKA subarray definition is exclusive (i.e. one antenna or station can only be part of one subarray), this will be achieved by defining a unique subarray formed by the whole SKA array, with the beamforming limited to the inner core by applying zero weights to the external antennas or stations.

For broadband or dual band observations, more than one subarray may need to be defined, typically 2 or 3. Ideally these subarrays will be configured as partitions of the core subarray, producing VLBI beams with similar FoV and sensitivities, taking into account the different observing wavelengths. SKA1-MID is able to provide the same number of VLBI beams for each configured subarray without consuming additional processing resources, up to the maximum of 52 beams for each of the 16 subarrays, that is the maximum number of subarrays allowed for SKA. But SKA1-LOW would be limited to a maximum of 16 VLBI beams in total to be shared among the 16 subarrays. SKA imaging products will be provided from each of these subarrays. In this case it will not be possible to provide imaging products from the whole array, just from a partial array formed by one of the core partitions and the external to the core elements.

For some SKA-VLBI projects, in addition to the VLBI beams produced from the phased-up core, it may be advantageous to include individual SKA antennas or stations in the VLBI network. The individual elements provide short uv-spacings for imaging and calibration, freeing up SKA resources for local imaging. The SKA arrays will be able to provide a total of 15 elements that are considered as individual subarrays formed by just one element. The SKA correlators will beamform single elements providing effectively the primary beams of the antennas or stations, properly channelized in VDIF format. The number of individual elements and their bandwidth will be ultimately limited by the available network connection to the VLBI correlator as data rates increase considerably. A detailed study of the possible

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configurations is given in the JUMPING JIVE deliverable D10.4 “Report on SKA-VLBI Key Science Projects” [RD19].

7.5 SKA-VLBI Science Operations

Science Operations in the SKA Observatory are divided into three phases: Phase 1 for announcement of opportunities, scientific proposal preparation, submission, review and time allocation, Phase 2 when a successful proposal becomes a project and the observation is scheduled and executed, and Phase 3 when the observed data is processed to generate the data products, that are provided to the scientists. The following sections give an overview of these three phases for the SKA-VLBI observations, and outline the outstanding issues that would require agreements between the SKA Observatory and the SKA-VLBI Consortium, once the SKA access policies have been established.

7.5.1 Science Operations Phase 1

Announcements of opportunities for SKA-VLBI observations would need to be coordinated between the SKA and the SKA-VLBI Consortium members. If feasible and efficient, observing windows will be chosen to allow for adequate proposal review and time allocation at all participating facilities. The announcements will also specify the capabilities and observing modes offered. Proposals will need to be submitted to both the SKA Observatory and the SKA-VLBI Consortium.

The Consortium will forward the proposal to the requested networks for scientific and technical assessment. The proposal handling, review and time allocation process will be decided by the different VLBI stakeholders, most probably based on the agreements that are currently in place for VLBI global observations (section 3.2). The SKA-VLBI Consortium members may provide specialised support for SKA-VLBI proposals preparation. All proposals will be eligible at the different VLBI networks based on their open sky models. The number of approved projects will be effectively limited by the VLBI networks available for SKA co-observing.

For VLBI networks or facilities that are not members of the SKA-VLBI Consortium an equivalent process will need to be put in place for announcement of opportunities, proposal handling, review and time allocation.

Requests for SKA-VLBI time will also be submitted to the SKA Observatory as coordinated proposals that may require standard or time-critical observations, including triggers and ToO observations. SKA-VLBI observations will be available for the three main types of SKA projects: Principal Investigator (PI) and Key Science Projects (KSPs) for members and Open Time (OT) for all observers.

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In addition to the basic proposal constituents, proposals requesting the SKA-VLBI capability would need to include:

- The list of the coordinated facilities requested in the observation.
- Proper justification for the SKA participation.
- Number of SKA VLBI beams, subarrays and their characteristics. There would be a number of templates available to guide with this selection. As SKA resources may change over time and are not guaranteed for the observing date (up to 5% antennas/stations could be down for maintenance or repair), the VLBI proposals need to specify the minimum sensitivity (number of antennas or stations) and resolution (maximum baseline length) required in the SKA subarrays.
- VOEvents rules if they may trigger events during its observation, internal or external to SKA.
- VLBI projects should include appropriate Quality Assessment (QA) rules. VLBI projects are not usually stopped or aborted due to adverse weather conditions or data quality assessments, unless prescribed by SKA safety procedures.
- Simultaneous SKA observing modes required for every configured subarray.
- VLBI proposals may indicate specific SKA commensality possibilities but this is not mandatory.

The SKA Observatory will peer review VLBI proposals following its established access rules and regulations, based on their scientific merit and technical feasibility.

Successful proposals from members of the SKA-VLBI Consortium will need approval from both the SKA and the Consortium members participating in the observation. Time allocation would necessarily need to be coordinated between the SKA Observatory and those observatories/stations taking part in the VLBI observations. Grades assigned to proposals may require normalisation between all partners, or other agreements, to decide time allocation priorities. After this process, the approved SKA-VLBI projects would be those with crucial SKA participation to achieve the scientific goals.

Certain exceptionally important SKA-VLBI time critical projects may be given override status by consensus. For the SKA, a project with override status is immediately scheduled and executed when the triggering conditions are met, displacing any projects currently being observed if those resources are required. For VLBI networks others than the VLBA, rapid responses are really challenging and may only be possible if a VLBI observation is already being performed, and under certain circumstances (same observing band, etc.). Future VLBI facilities are likely to be dynamically scheduled, such as the African VLBI Network (AVN), allowing for greater flexibility to support time critical projects.

For the particular case of Target of Opportunity (ToO) proposals, prompt coordinated action from the SKA Observatory and the SKA-VLBI Consortium members would be necessary for evaluation and time allocation.

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7.5.2 Science Operations Phase 2

Phase 2 of Science Operations starts when a successful SKA-VLBI proposal is approved and becomes a project. In this phase, we may differentiate between scheduling, preparation and execution of an observation. While observing, program changes may occur in response to time critical projects.

SKA-VLBI observations scheduling phase

The SKA Observatory will perform 24h flexible observing using dynamic scheduling to react quickly and efficiently to changing environmental conditions, availability of resources and capabilities, and other operational or scientific needs. VLBI projects need to be scheduled on fixed dates and times for proper coordination of the participating radio telescopes and VLBI networks. The SKA-VLBI Consortium members and the SKA Observatory would need to define adequate project lifetimes and compatible observing windows, to be able to properly schedule VLBI projects. The VLBI schedulers and the SKA science operations group will agree on observing dates taking into account all known constraints at the observatories. Ultimately, the SKA-VLBI Consortium members will ensure that the required VLBI network, global or not, is coordinated and scheduled to successfully achieve the goals of the project, and that an appropriate VLBI correlator is chosen, following the VLBI global model.

Another main constraint for scheduling is that the VLBI networks usually do not operate 24/7 and need staff, either physically at the radio telescopes or working remotely, to perform the observations. For the particular case of real-time VLBI observations (e-VLBI) staff from all the radio telescopes and the correlator need to attend simultaneously, constraining the possible observing dates.

SKA-VLBI observations preparation phase

Once a SKA-VLBI project has been scheduled, the PI will be notified and asked to prepare the VEX file. The PI will be guided on how to prepare the VEX file to correctly phase-up the SKA subarrays, including phasing scans with a certain cadence depending on the observing frequency and weather, select calibrators with appropriate characteristics for phasing-up, etc., and to include appropriate pre-observation calibrations. There will be SKA subarray templates available to help with the design of the observations. For the duration of the project the SKA Observatory will assign a “Friend of Project” (FoP) who will serve as the point of contact for PIs, to answer project-specific questions. The SKA-VLBI Consortium members may assist the FoP in this task.

Due to the complexity of the VLBI observations, it is advisable that participant VLBI networks make sure the VEX file prepared by the PI is correct for all facilities and the revised version

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will be made available in a SFTP file server or similar. Usually radio telescopes participating in a VLBI observation need to retrieve and process the VEX file themselves. For the particular case of the SKA, the VLBI project will have its own container in the SKA Observation Design Tool, and the PI will retrieve the verified VEX file and attach it to the container. Any other additional information received from the VLBI correlator, such as the correlator destination IP addresses for transfer of the VLBI data, should also be included in the VLBI project container. The SKA scheduling block (SB) will be generated using the VLBI VEX file and the additional information. The scheduling blocks have all the information necessary to configure the SKA telescopes, perform the VLBI observations, process the data to extract the required science data products, and send the data to the VLBI correlators and the SKA Regional Centres. SKA allows for minor VEX file amendment a few hours before the start of an observation, with automatic generation of the corrected SB.

During the VLBI observation preparation phase, the SKA Observatory will decide potential commensality with other SKA projects, if the available resources allow for it. Commensality may alter the scheduling priorities for some lower ranked projects that will inherit the scheduling priority of the project they are piggy-backing onto. VLBI projects are compatible with all types of SKA commensal observing, only limited by the available resources. The commensality concept could be adopted by the VLBI networks in the near future, when the same VLBI data products are accessed by several projects to achieve different scientific goals. The different commensal possibilities may need to be explored by the SKA Observatory and the SKA-VLBI Consortium members.

The SKA-VLBI observations require appropriate scheduling of different SKA and VLBI resources. The SKA Observatory will need availability of the CSP and the SDP processing resources and data transfer between them, and the VLBI recording buffer. The SKA will also require sufficient bandwidth on the external data networks to stream data to the correlator and to the SRCs. On the other hand, VLBI network resources include VLBI operational equipment and recording buffer at the participant radio telescopes, NREN data networks usage, appropriate correlator recording buffer and processing resources.

The exact usage of these resources depends on the specific SKA-VLBI project, for example if the project requires real-time correlation or not. Electronic e-VLBI will usually be necessary for time critical projects that require fast turnaround of the results and imply both real-time e-transfer of the data to the correlator and real-time correlation. For standard observations, the data will usually be recorded at the SKA VLBI terminal and will be transferred after the observation, but it may also be transferred to the correlator in real-time and stored there until correlation.

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SKA-VLBI observations execution phase

Once resources are available the observation will commence at the scheduled time. Usually VLBI observations reserve a certain amount of time before the first target to perform different health checks and calibrations, such as pointing, system temperature and efficiency measurements or fringe tests on a calibrator. For the SKA telescopes, all these calibrations will need to be included in the VEX file.

During the observations, the SKA VLBI equipment is automatically controlled and monitored using the Tango framework, an open source monitor and control framework adopted for the SKA telescopes. For more details on the VLBI equipment Tango development refer to the JUMPING JIVE deliverable “Details on VLBI Interfaces to SKA Consortia” [RD01, RD05]. The SKA operator will supervise the proper configuration and functioning of the VLBI equipment through graphical interfaces or GUIs, as done for the other SKA subsystems.

In the event of problems, the SKA operator will open tickets using the SKA Problem Reporting and Tracking System that notify the appropriate specialists, which could include nominated SKA-VLBI Consortium members staff, mainly the staff from the VLBI correlators. VLBI observations are not usually halted or aborted due to adverse weather conditions or data quality assessments, unless prescribed by the radio telescopes safety procedures. The VLBI scheduling blocks (SBs) need to be executed at a fixed time and cannot be repeated at another time. For an SB that has already started that is halted by the SKA operator, whenever continued, the execution needs to jump to an appropriate time in the near-future and start executing at the right time.

During e-VLBI observations, real-time decisions may need to be made by the VLBI correlator staff, such as halting the data transfer in case of network overflow or use of a different correlator server. The VLBI correlator staff will have remote access to the VLBI terminal to be able to control these functions. Fluid communication will be needed with the SKA operator during VLBI observations.

Observing program real-time changes and time critical programs

The SKA and the VLBI networks may be subjected to real-time schedule changes in response to higher priority triggered projects or Targets of Opportunity proposals. Whenever this happens, the VLBI observation being executed could be aborted only at some facilities or completely aborted for all participants. These real-time decisions need to be properly communicated between the participant facilities. Aborted projects or projects impacted by technical problems, weather, quality assessment rules, etc. may need to be re-scheduled and re-observed as decided by the SKA Observatory and the SKA-VLBI Consortium members. Usually for VLBI observations the total observing time cannot be recovered from different observing dates, and the whole observation would need to be repeated as initially designed.

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Considering the complexity of constraints for scheduling SKA-VLBI observations on a global scale, all parties should make an effort to keep observing interruptions to a minimum.

In the particular case that the triggered observation is another VLBI observation that has already been approved with higher priority than the one being executed, the observing program could be modified in real-time. The time slot could be used for the VLBI triggered project, with a prompt delivery of a new VEX file. The VEX file can be quickly generated from a generic file, (i.e. the key file), previously prepared by the PI. The new SB will be automatically generated and executed. It may however be expected that only the highest graded SKA-VLBI projects will be supported by the SKA, therefore it is very unlikely that a regular VLBI project will override another SKA-VLBI observation (unless it is a triggered SKA-VLBI project itself).

A possible source for triggers are the SKA1 telescopes. The SKA-VLBI Consortium members would need to establish routes to be able to trigger VLBI observations from SKA triggers, subscribing to the SKA alerting system, most probably using VOEvents or similar. It is unlikely that the VLBI correlator will trigger the SKA, but the possibility should be further explored. One form of triggering could be the initial detection of candidate calibrators that appear compact on long baselines, and inform the SKA to form beams at those positions. In any case, it will be important to properly define the triggers, their effective cadence and expiration date, response time to the triggers, observing modes offered and limitations, and override rules. The SKA could react to the trigger downloading the transient buffer if this was specified in the VLBI proposal, and they could also modify the executed program in real-time as mentioned before. Future VLBI networks will be able to quickly react to triggers, adapting their observing programs in real-time, but current networks have a typical response time to critical events of the order of several days.

7.5.3 Science Operations Phase 3

During phase 3 the observed data is processed to generate the data products that are provided to the scientists. Appropriate proprietary periods and a data management plan need to be established, as well as outreach strategies.

Data processing and rights, proprietary periods and data management plan

After observation completion, the VLBI project container will include SKA metadata, the SKA observing log and any tickets opened due to problems. Transfer of the VLBI data may have been performed during the observation or will be scheduled at a later time, whenever coordinated with the nominated VLBI correlator. Specific logs and metadata collected by the VLBI terminal are also transferred together with the VLBI data. These ancillary data products

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are described in detail in the TM to VLBI Interface Control Document [RD05, RD01]. The data transfer can be initiated automatically or by the SKA operator.

VLBI correlation may have happened in real-time for e-VLBI observations and visibilities made available almost immediately to the PI. But for standard observing, VLBI correlation needs to wait until the data from all participating facilities has been e-transferred or shipped via courier. Once correlation is completed, the VLBI visibilities are provided to the PI, with a proprietary period that depends on the project type: regular, triggered or target of opportunity. These proprietary periods are similar for the VLBI networks and, whenever collaborating together, the nominated correlator rules are usually adopted. VLBI networks assume PI responsibility for calibration, imaging and analysis of the observations. Usually the networks support the PI on the different phases on the project, and some networks provide automated pipelines to help with the data reduction. After a certain period of time, mostly depending on the VLBI correlator buffer availability, data from all participating facilities is deleted. This will include the SKA VLBI beams voltage data. Only VLBI visibilities are long-term archived and made public once the PI proprietary periods have concluded.

If the VLBI observation also requested other SKA Observatory Data Products (ODP), such as SKA Imaging and polarimetry, transient and pulsar search, etc., SDP data processing will commence whenever scheduled. The SDP has sufficient processing resources and different levels of data buffers to be able to process data from different observing modes, subarrays and commensal projects in parallel, with limited functionality depending on the project's complexity. SDP calibrated and science-ready data products will be transferred to the SRCs, from where the PI will access them. For follow-up and time critical projects that need fast turnaround of the results, SKA science data products and VLBI products will be provided on an appropriate timescale, limited by the observing capacities.

The SRCs may also produce Advanced Data Products (ADP) for VLBI. ADPs for VLBI are being defined by the SKA Science Working Groups. Both types of products are the property of the SKA Observatory and are subject to the SKA proprietary period which once completed are made publicly available. For SKA-VLBI projects the SKA Observatory and the SKA-VLBI Consortium members may need to decide the synchronisation of the proprietary periods.

Publications and media communication strategy

Scientific and technical research made possible thanks to the SKA-VLBI capability should properly acknowledge the participation of all the research institutions and funding agencies. In this respect, additional decisions may be needed by the SKA and the SKA-VLBI Consortium members, such as to respect each other's brands, coordinate public communications, press releases and embargos, public engagement strategies, etc.

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7.6 SKA-VLBI Engineering Operations

Engineering Operations comprise those activities necessary for the installation, maintenance and development of the VLBI equipment for the SKA Observatory. A detailed description of the VLBI equipment and the different interfaces with the SKA subsystems is described in the JUMPING JIVE deliverable “Details on VLBI Interfaces to SKA Consortia” [RD01]. The VLBI equipment has been designed to be fully integrated into SKA Operations as any other SKA subsystem, for monitor and control functions by the SKA Observatory.

The VLBI equipment will be installed at the SPC located in Perth and Cape Town, to avoid harmful radio interferences at the telescope sites and to allow easy access by the SKA-VLBI Consortium. These supercomputing centres, provided by the SKA Hosting countries, will also host one of the key components of the SKA Observatory, the SDP. The SKA requirements for the SPCs will need to specify requirements for the installation and maintenance of the VLBI equipment.

For SKA Engineering Operations, it is assumed that the VLBI equipment is considered part of the SKA equipment, although provided by a different budget source. Therefore, the VLBI equipment will be subjected to SKA configuration control rules and will be included in the SKA Product Breakdown Structure (PBS) with appropriate number of spares provided by the SKA-VLBI Consortium members. It is also assumed that the installation, comprising its different aspects such as assembly, integration and verification (AIV), and the commissioning and science verification activities will be primarily performed by the SKA Observatory with the support of the SKA-VLBI Consortium members.

The SKA has very stringent availability requirements, with an operational availability of at least 95%. The VLBI equipment will need to conform to this availability, but its accountability could be just limited to the agreed observing periods. The number of spares and maintenance level will need to be decided in order to fulfil the availability requirements for the VLBI equipment.

The VLBI equipment design is based on modular Line Replaceable Units (LRU), such as the replaceable recorder buffer hard disks. From previous experience with this type of systems, occasional maintenance support will be required by a non-specialised technician for LRU replacement. The LRU level maintenance for the VLBI equipment is assumed to be included in the SKA engineering operations, with guidance from the SKA-VLBI Consortium members.

Major maintenance of the VLBI terminal, such as software and hardware upgrades or major repairs, will be responsibility of the SKA-VLBI Consortium members. These activities will be performed by a technician with appropriate expertise, either from remote or locally. Local specialised support at the SPCs could be contracted out by the SKA-VLBI Consortium members.

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7.7 SKA-VLBI Operations Model Assumptions

This section summarizes the assumptions made for the elaboration of the SKA-VLBI Operations Model presented in this study (Table 3). These assumptions will have to be verified and approved by the different stakeholders.

Table 3. List of assumptions made for the elaboration of the SKA-VLBI Operations Model.

SKA-VLBI Operations Model Assumptions		
Assumption #	Title	Description
Operational Principles (Section 7.2)		
1	Existence of a SKA-VLBI Consortium	The SKA-VLBI Consortium is envisioned as a collaboration between the SKA Observatory and different VLBI networks and observatories, not necessarily global, with the purpose to provide support for the SKA-VLBI capability and coordinate the VLBI networks for joint observations with the SKA, based on the current model for VLBI global observations.
2	SKA-VLBI Consortium Agreements	The SKA-VLBI Consortium may not be a legal entity and individual agreements (MoUs) between the SKA Observatory and the different VLBI networks or VLBI observatories would be needed for this joint collaboration.
3	SKA relationship with the VLBI networks	The existence of this Consortium will not prevent other agreements between the SKA and the VLBI networks for further collaboration.
4	SKA-VLBI Consortium responsibilities (I)	The SKA-VLBI Consortium members will develop and provide the VLBI equipment (including appropriate hardware and software) and spares required by the SKA telescopes to enable VLBI observations.
5	SKA-VLBI Consortium responsibilities (II)	The Consortium members will support the SKA with the installation and commissioning, science and engineering operations, and decommissioning of the VLBI equipment.
6	SKA-VLBI Consortium responsibilities (III)	The Consortium members will equip the VLBI correlators with the appropriate buffer and software to support the SKA telescopes.

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7	VLBI equipment availability for non-Consortium members	For occasional use, it is expected that the VLBI equipment provided by the SKA-VLBI Consortium will be available for all SKA projects requesting the VLBI observing mode regardless if the participant VLBI networks and observatories are part of the Consortium. For more regular use, participation in the SKA-VLBI Consortium would be encouraged.
8	SKA Observatory Development Programme	The SKA Observatory may choose to use this programme to enhance its VLBI capability. Coordination with the SKA-VLBI Consortium members will be required to assure compatibility.
Science Operations (Section 7.5)		
Science Operations Phase 1 (Section 7.5.1)		
9	Announcements of opportunities	Announcements of opportunities for SKA-VLBI observations would need to be coordinated between the SKA and the SKA-VLBI Consortium members, specifying the capabilities and observing modes offered. Observing windows will be chosen to allow for adequate proposal review and time allocation at all participating facilities.
10	SKA-VLBI Consortium responsibilities (IV)	The SKA-VLBI Consortium members may provide specialised support for the preparation of SKA-VLBI proposals.
11	SKA-VLBI proposals submission	Proposals will need to be submitted to both the SKA Observatory and the SKA-VLBI Consortium, and other facilities as appropriate.
12	VLBI proposal handling, review and time allocation	The Consortium will forward the proposal to the requested networks for scientific and technical assessment. The proposal handling, review and time allocation process will be decided by the different VLBI stakeholders, most probably based on the agreements that are currently in place for VLBI global observations.
13	Announcements of opportunities, proposal handling, review and time allocation for non-members	For VLBI networks or facilities that are not members of the SKA-VLBI Consortium an equivalent process will need to be put in place for announcement of opportunities, proposal handling, review and time allocation.
14	Successful proposals	Successful proposals from members of the SKA-VLBI Consortium will need approval from both the SKA and the Consortium members participating in the observation.

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15	Time allocation	Grades assigned to proposals may require normalisation between all partners, or other agreements, to decide time allocation priorities.
16	Override status	Certain exceptionally important SKA-VLBI time critical projects may be given override status by consensus.
17	ToO proposals	A prompt coordinated action from the SKA Observatory and the SKA-VLBI Consortium members would be necessary for evaluation and time allocation of ToO proposals.
Science Operations Phase 2 (Section 7.5.2)		
18	Scheduling	The SKA-VLBI Consortium members and the SKA Observatory would need to define adequate project lifetimes and compatible observing windows, to be able to properly schedule VLBI projects.
19	SKA-VLBI Consortium responsibilities (V)	The SKA-VLBI Consortium members will ensure that the required VLBI network, global or not, is coordinated and scheduled to successfully achieve the goals of the project, and that an appropriate VLBI correlator is chosen, following the VLBI global model.
20	SKA-VLBI Consortium responsibilities (VI)	The SKA-VLBI Consortium members may assist the SKA FoP in answering the PI about project-specific questions.
21	SKA-VLBI Consortium responsibilities (VII)	Due to the complexity of the VLBI observations, it is advisable that participant VLBI networks make sure the VEX file prepared by the PI is correct for all facilities. The verified version will be made available to the PI.
22	VEX file handling	The PI will attach the verified VEX file to the VLBI project container in the SKA Observation Design Tool.
23	Commensal observing	The different commensal possibilities may need to be explored by the SKA Observatory and the SKA-VLBI Consortium members.
24	SKA-VLBI Consortium responsibilities (VIII)	In the event of problems, the SKA operator will open tickets using the SKA Problem Reporting and Tracking System that notify the appropriate specialists, which could include nominated SKA-VLBI Consortium members staff, mainly the staff from the VLBI correlators.
25	Observing program real-time changes	Real-time decisions need to be properly communicated between the participant facilities.

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26	Conditions for re-observing	Aborted projects or projects impacted by technical problems, weather, quality assessment rules, etc. may need to be re-scheduled and re-observed as decided by the SKA Observatory and the SKA-VLBI Consortium members.
27	SKA triggers	The SKA-VLBI Consortium members would need to establish routes to be able to trigger VLBI observations from SKA triggers, subscribing to the SKA alerting system.
Science Operations Phase 3 (Section 7.5.3)		
28	Proprietary periods	For SKA-VLBI projects the SKA Observatory and the SKA-VLBI Consortium members may need to decide the synchronisation of the proprietary periods.
29	Publication and media communication strategy	Different decisions may be needed by the SKA and the SKA-VLBI Consortium members in this respect.
Engineering Operations (Section 7.6)		
30	SPCs SKA requirements for VLBI	Requirements for installation, maintenance and access to the VLBI equipment to be included in the SKA requirements for SPCs, following SKA-VLBI Consortium members' guidelines.
31	VLBI equipment considered part of SKA	VLBI equipment will be subjected to SKA configuration control rules and will be included in the SKA Product Breakdown Structure (PBS) with appropriate number of spares, that are provided by the SKA-VLBI Consortium members.
32	VLBI equipment installation and commissioning	The installation, comprising its different aspects such as assembly, integration and verification (AIV), and the commissioning and science verification activities will be primarily performed by the SKA Observatory with the support of the SKA-VLBI Consortium members.
33	SKA availability requirements	The VLBI equipment will need to conform with SKA availability requirements, but its accountability could be just limited to the agreed observing periods. The number of spares and maintenance level will need to be decided in order to fulfil the availability requirements for the VLBI equipment.
34	LRU level maintenance	The LRU maintenance level for the VLBI equipment, performed by a non-specialised technician, is assumed to be included in the SKA Engineering Operations, with guidance from the SKA-VLBI Consortium members.

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35	SKA-VLBI Consortium responsibilities (IX)	Major maintenance of the VLBI terminal, such as software and hardware upgrades or major repairs, will be responsibility of the SKA-VLBI Consortium. These activities will be performed by a technician with appropriate expertise, either from remote or locally. Local specialised support at the SPCs could be contracted out by the SKA-VLBI Consortium members.

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ANNEXES

ANNEX 1: VLBI Networks Operational Models

ANNEX 1.1: The Australian Long Baseline Array (LBA)

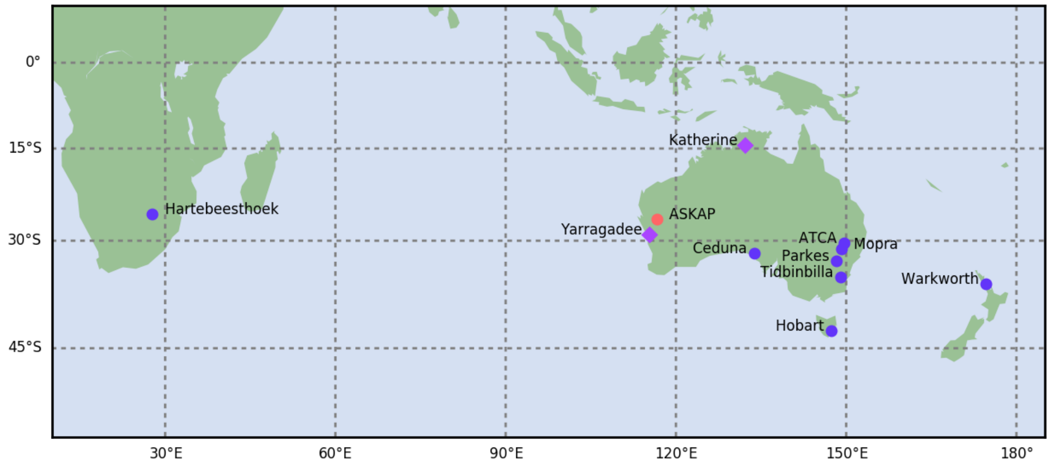

Figure 5. The Australian Long Baseline Array (LBA) VLBI network.

The Australian Long Baseline Array (LBA) [RD11] is the only VLBI network located in the Southern Hemisphere, with telescopes across the Australian landmass as well as South Africa and New Zealand (Figure 5). The array offers unique access to sources of astronomical interest that are located in the southern sky and it can be used for any project that requires high resolution at radio frequencies (up to few milliarcseconds). SKA1-MID and LOW will be excellently located to contribute to the LBA observations, adding very sensitive elements to this network.

Currently the LBA utilises the Australia Telescope National Facility (ATNF) telescopes Parkes and ATCA (lately Mopra participation is uncertain), and the Hobart and Ceduna antennas operated by the University of Tasmania. Other telescopes may be also requested subject to their availability, as the AuScope geodetic telescopes Yarragdee and Katherine and the telescopes from the NASA's Deep Space Network facility at Tidbinbilla. The Hartebeesthoek telescope in South Africa and the Warkworth telescope in New Zealand are also regular partners. In the past a single ASKAP antenna with a single pixel feed also participated in LBA observations but at the time of writing this is not currently available.

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The LBA observes approximately 21 days per year (~ 500 hours), divided in 2 semesters, Semester I runs from April until the end of September and Semester II from October until the end of March. The Call for Proposals is made by ATNF twice a year under open skies principles, with deadlines in mid-December and mid-June, for the following observing semester. Time critical observations can be proposed following the standard ATNF procedures for ToO and NAPA (triggered) requests, but fast response from the network is not usually provided. Proposals for observing time are only accepted via OPAL, the ATNF online proposal tool, and are reviewed by the ATNF TAC. Time is allocated on the basis of scientific merit. The TAC meeting is usually held 6 weeks after the proposal deadline.

LBA uses a fix scheduling system imposed by the required coordination of the different facilities. Schedules are typically released one month before the beginning of the semester. Time is blocked out for LBA observations when the schedules for each semester are made, but detailed LBA schedules are determined closer to the time of each LBA block, and the PIs of scheduled observations are contacted at that time. LBA accepted proposals are active for a whole year, counting from the semester that it was approved. If the project cannot be scheduled within one year it will lapse and will need to be resubmitted. ATNF ToO or NAPA projects may displace LBA observations and observers have no special rights to the data, but a reasonable attempt will be made to replace time lost due to override or to equipment failure.

LBA projects have the usual ATNF 18-month proprietary period from the observing date.

LBA brief technical description

The current capabilities of the LBA are briefly outlined below:
The disk-based recording system is used for all recorded VLBI observations. A bit rate of 256 Mbps (2 channels of 16MHz bandwidth for both polarisations, with 2-bit digitisation and Nyquist sampling) can be sustained at all LBA telescopes and is the standard observing mode using the ATNF LBA DAS backend. Data rates up to 1 Gbps can be achieved at most stations but clear justification for the requested rate must be made.

Real-time e-VLBI observations are possible with some combination of LBA telescopes.

All recorded observations are correlated with the DiFX software correlator installed at the Pawsey Supercomputer Centre. The software correlator is capable of correlating the high data rate observations at high spectral resolution with arbitrary correlator integration times.

ATCA is capable to operate in a hybrid mode, to participate in VLBI observations and to provide local interferometry data for a source that is not in the monitoring program, simultaneously, for calibration purposes.

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LBA constraints

There are several constraints when using or collaborating with the LBA network that need to be considered:

- When the schedules are released the cover sheets and observations table of proposals that were successfully allocated observing time are made publicly available through OPAL and the SAO/NASA Astrophysics Data System (ADS). The scientific justifications are not made publicly available.
- Once scheduled, a wiki page is created for the experiment, with all the information (setup, schedules, log files, weather data, calibration data, etc.). Most of this information is provided by the participating antennas.
- The PI needs to submit to an ftp site the schedule files ~2weeks before the start of the LBA scheduling block (on monthly basis). The PI needs to use SCHED and the standard LBA setups for continuum observations or ask for advice to ATNF staff for spectral line or more complex observations. The PI is responsible for including in the schedules real-time and during the observation fringe finder scans, phase calibrator sources scans, ATCA re-phasing scans, ATCA flux calibrator scans, etc.
- Observers are expected to support the LBA observing effort monitoring their observations, either remotely, after appropriate training has been received, or in person at the SOC in Sydney. Support for correlation is no longer needed.
- Calibration, Imaging and Analysis is responsibility of the PI, but user support is available, including assistance with proposal preparation, scheduling, observing and data reduction.
- Time critical projects (ToO and NAPA) scientific results should be made publicly available as soon as possible via an appropriate astronomy alert service (e.g. IAU Circular, Astronomers Telegram, Gamma Ray Burst Coordinated Network (GCN). If results are not made available within a week of the observations, proprietary rights will be suspended, and the raw data may be released to other groups.

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ANNEX 1.2: The European VLBI Network (EVN)

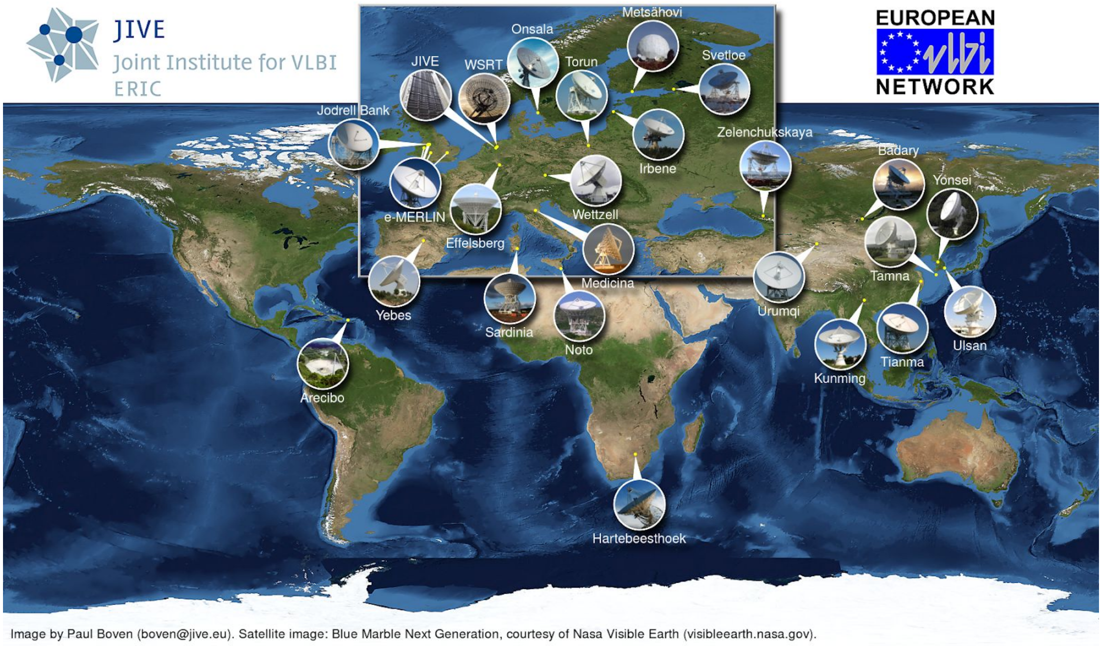

Figure 6. The European VLBI Network (EVN).

The European VLBI Network (EVN) [RD12] is a network of radio telescopes located primarily in Europe and Asia, with additional antennas in South Africa and Puerto Rico, which performs very high angular resolution observations of cosmic radio sources. It has a vantage situation for collaboration with the SKA1-MID and SKA1-LOW telescopes. The EVN is the most sensitive VLBI array in the world, capable of performing real-time observations. The network is the result of a collaborative effort between different countries and research institutes and operates as an "open skies" facility.

The EVN issues calls of proposals 3 times a year, with deadlines on the firsts of February, June and October, except for Target of Opportunity (ToO) and Short Observation proposals, which can be submitted any time. It offers different observing possibilities: 3 observing sessions per year (3-4 weeks long each with 3-4 different observing frequencies), 10 real-time e-VLBI sessions per year (24-h each, almost monthly) and possibility to schedule out-of-session observations on user specified dates (no more than 10 times/year, up to 144h/year). The EVN proposals may also request joint e-MERLIN and EVN observations for improved uv-coverage at short spacings and global VLBI observations when the EVN observes jointly with NRAO/GBO telescopes or with the Long Baseline Array, for improved uv-coverage at the longer baselines. Details on these collaborations are given in a following section.

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For proposal submission, the observer should use the NorthStar submission tool. There are three types of proposals: regular (which include standard disk observations, e-VLBI, trigger, and out-of-session, including other VLBI networks), ToO and short observation proposals. The network also performs Network Monitoring Experiments (NME) to test new observing modes or receivers and single dish calibration runs. Proposals are assessed by the EVN Programme Committee three times a year and if approved are active for 1 year. Support for proposal preparation, scheduling, and correlation of EVN projects is provided by the Joint Institute for VLBI ERIC (JIVE). JIVE staff are also able to support EVN users with data analysis, for the best science to emerge. Proprietary period for the EVN is 12 months after distribution of the data to the PI.

EVN brief technical description

EVN observations may be conducted with disk recording (standard) or in real-time correlation (e-VLBI). Standard EVN observations are available at wavelengths of 92, 50, 30, 21/18, 13, 6, 5, 3.6, 1.3 and 0.7 cm. e-VLBI observations can be performed at 21/18, 6, 5, and 1.3 cm. e-MERLIN can be combined with the EVN in both standard and e-VLBI observations. Global observations are performed only with standard observations.

Disk recording or e-VLBI at 2 Gbps is available on the majority of EVN telescopes and at most of the observing bands. The remaining telescopes will record at 1 Gbps or the highest possible bit-rate (mixed mode observation).

The EVN uses continuous calibration (modulation of the noise diode at 80Hz) or on/off noise diode calibration before (and after) the scan (FS preob and postob).

The EVN has implemented a scheme in which projects with high priority can be executed within 24h of a trigger if it occurs during/before a scheduled real-time e-EVN observation. They can be triggered by e-mail requests to the PC chair. A basic procedure for automated EVN triggering of projects on even shorter timescales (order of 10 minutes) have been worked out but is not operational yet.

EVN constraints

Observatories part of the EVN should comply with the *Permanent Action Items* list (former Bologna rules), mainly:

- Each observatory participates in the structure and management of the EVN: Consortium Board of Directors, Programme Committee and the Technical and Operations Group, appointing appropriate people for each body and participating in the regular meetings.
- The block schedule is frequently updated, changes or errors should be communicated to the EVN scheduler asap.

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- The EVN disk-pack pool should be increased by each station by 7000 €/year.
- Stations should ship recorded disk packs back to the correlator within a week after the completion of the observing session. Stations are to register incoming and outgoing disk packs using NRAO PACKTRACK application.
- Stations should keep technical information up-to-date (EVN status table, SCHED frequency catalog, EVN TOG wiki page, etc.) and subscribe to the EVNTech e-mail exploder.
- GPS vs. frequency standard (H maser) data should be updated on VLBEER preferable on a daily basis. Measurements should be made during the observations and written to the observation log.
- Session preparation: the scheduler will advise whenever the VEX files are ready for download, follow disk packs handing and conditioning procedures, ensure that local FS procedures are up-to-date and run the FS diagnostic tests.
- During the sessions: use the single dish calibration runs (CL sessions) to update any calibration parameter (noise diode, gain curves and DPFU, SEFD, etc.), send feedback on individual observations via the EVN Feedback facility, observing logs – or dummy logs for failed observations- are to be transferred to the ftp area (VLBEER server) within 72h after completion, or asap for e-VLBI observations (<24h).
- Post session feedback: Stations must aim to produce ANTABFS-, UVFLG- and RXG-files within 2 weeks after the end of a session, and asap for e-VLBI and NME observations. All stations should look at pipeline results available from the EVN data archive pages at JIVE, in particular amplitude corrections found by selfcal on strong and compact calibrators, to check whether the amplitude correction factors are unreliable.
- Post-processing: ANTAB and UVFLG files produced by the JIVE Support Scientist (after post-processing of calibration and log files from stations) should be made available on VLBEER 1 week after correlation of the corresponding project (1 day after correlation for the case of e-VLBI projects).
- Stations participating in e-VLBI observations to make sure to follow “e-VLBI station recommendations”: operator to use Mattermost chat in real-time to communicate with the correlator (JIVE staff), make sure the correct versions of the different software packages are installed, start jive5ab application before the observation, and configure FlexBuffs for automated transfers.
- EVN spare parts: Make sure that your station invests in EVN spare parts. Directors agreed that each institute should invest ~3000 € in spare parts.

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ANNEX 1.3: The East Asian VLBI Network (EAVN)

Figure 7. The East Asian VLBI Network (EVN).

The East Asian VLBI Network (EAVN) [RD13] is a collaboration between China, Japan and Korea to perform joint VLBI observations realising a quite unique VLBI network in the world. Currently consists of 11 radio telescopes, the Korean KVN and the Japanese VERA network (KaVA) and some additional Chinese and Japanese antennas. New additions are be expected soon that will improve its performance. Their main observing wavelength is the centimetre and sub-centimetre regimes, but efforts have been initiated to cover lower frequencies, as it is very well located for collaboration with the SKA1-LOW telescope. Collaboration with SKA1-MID will be facilitated through Global observations with the EVN.

The EAVN has been offering open-use time on share-risk basis since 2018, in a dual semester scheme, with call for proposals in June and November. Semester A runs approximately between mid-January until mid-June, while semester B starts in September and runs until mid-January. Not all the telescopes are available throughout these periods.

Proposals in latex format need to be submitted through the EAVN website. If the proposer is not familiar with the EAVN it is recommended to include one collaborator from the network. The EAVN accepts regular, large programs and target of opportunity proposals (ToO). Large

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Program can request up to 150h per project (or less if including non-KaVA antennas) as long as they do not conflict with existing KaVA Large Programs. Target of Opportunity proposals with a trigger criterion valid for one year are welcome at the regular call of proposals, and unexpected or urgent ToO can be submitted any time as Director's Discretionary Time (DDT) by e-mail, using same format as other proposals.

The proposals are assessed based on scientific merit. The TAC may decide just to grant KaVA observing time, so participation of the other EAVN telescopes need to be properly justified. The results of the review are announced to each PI approximately 1.5 months after the call for proposals' deadline. For successful proposals, users are requested to prepare the observing schedule file in VEX format two weeks before the observation date, with the support of a contact person in the EAVN Array Operation Center (AOC) and/or the assigned support scientist.

EAVN members take full responsibility for observation and correlation process, and thus basically proposers are not be asked to take part in observations or correlations. After the correlation, the user is notified where the data can be downloaded by e-mail. After one month of correlated data distribution to PIs, disk modules which contains raw observing data can be recycled without notice. For EAVN data reduction, the users are encouraged to reduce the data using the NRAO AIPS software package. The observation data and calibration data are provided to the users in AIPS compatible format.

The users who proposed the observations have an exclusive access to the data for 18 months after the correlation. After that period, all data for EAVN open-use observations is released as archive data, available upon request. This policy is applied to each observation, even if the proposed observation is comprised of multi-epoch observations in the observing session.

The EAVN organises a user's meeting and an East Asian VLBI Workshop every year.

EAVN brief technical description

The EAVN offers two observing frequencies: 22 (K-band) and 43 GHz (Q-band). The observations are basically limited to record with 1024 Mbps data rate, or a total bandwidth of 256 MHz, single polarisation (LHCP), with choice of 16 or 32 MHz channels covering the observed bandwidth. The data is recorded in different but compatible disk-based backends, OCTADISK, TMRT65 and Mark5B.

Correlation is performed with the FPGA based Korea-Japan Joint VLBI Correlator (KJJVC), the "Daejeon correlator". It is able to process a maximum of 16 antennas at once, with a choice of minimum integration times (from 0.2048 sec) and maximum number of output frequency channels (up to 8192 channels). The correlator outputs a FITS-IDI file.

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Amplitude calibration, performed by a hot load chopper wheel in most of the antennas, is accurate up to 15% or better at both K- and Q-bands.

EAVN constraints

There are several constraints when using or collaborating with the EAVN network that need to be considered:

- For a PI without EAVN experience, it is advised to add an EAVN collaborator to the proposal.
- The PI needs to submit the schedule file 2 weeks before the observing date.
- Schedules should contain usual delay and bandpass continuum calibrators scans, and maser sources or continuum gain calibrators for amplitude calibration.
- For the largest antenna pointing checks need to be regularly performed.
- Raw data may be deleted without advice one month after correlation.

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ANNEX 1.4: The Very Long Baseline Array (VLBA) and the High Sensitivity Array (HSA)

Figure 8. The Very Large Baseline Array (VLBA) and High Sensitivity Array (HSA)

The Very Long Baseline Array (VLBA) [RD14] is a network of 10 antennas of 25-m diameter. Currently only 50% of the operational time on the VLBA is available for “open skies” observing, with the other 50% allocated for use by the US Naval Observatory. The High Sensitivity Array (HSA) [RD15] uses the VLBA, plus the GBT, the phased VLA, and Effelsberg and Arecibo telescopes.

The National Radio Astronomy Observatory (NRAO) issues calls for proposals jointly for the Karl G. Jansky Very Large Array (VLA) and the Very Large Baseline Array (VLBA), the High Sensitivity Array (HSA), and the Global 3mm VLBI Array (GMVA), in February and August each year. Time on the VLBA and the HSA is scheduled on a 6-month semester basis. Semester A observations typically take place February through July and have an August 1 proposal deadline in the previous year; Semester B observations, take place from August through January and have a deadline on February 1. The GMVA observes just 2 weeks per year, one week in April, another in October, approximately.

Proposal preparation and submission are via the Proposal Submission Tool (PST) available through the NRAO Interactive Service web page. Three types of proposals may be submitted: regular proposals, large proposals and triggered proposals. Directors' Discretionary Time (DDT) proposals for a Target of Opportunity (ToO) or Exploratory Time may be submitted at any time. The NRAO Telescope Allocation Committee (TAC) make recommendations to the NRAO regarding time allocation and scheduling priorities of proposals submitted to the Observatory each semester, weighing science merit, technical feasibility, and programmatic concerns.

Most approved VLBA observations are performed dynamically; users must submit their observing (.key) files by e-mail before the beginning of the semester. Early submission of schedules maximizes the opportunity of dynamic observing and assists in the efficient scheduling of the VLBA.

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Standard NRAO 12-month proprietary period after the last observation was performed. NRAO offers extra staff assistance with VLBA observational setups and data reduction to new or novice VLBA users.

NRAO also facilitates access to a Joint Observing program with the XMM-Newton Project, the Chandra X-ray Observatory, the Hubble Space Telescope (HST), the Swift Gamma-Ray Burst Mission, and the Fermi Gamma-ray Space Telescope. For most of these collaborations each other TACs can award certain amount of time on the other facility. The observations are not required to be coordinated or simultaneous. But no observations, requiring simultaneous observation with both facilities, with a reaction time of less than 2 working days from an unknown triggering date will be considered for this cooperative program.

VLBA and HSA brief technical description

The VLBA operates two data systems, a Polyphase Filterbank (PFB), and a Digital Downconverter (DDC), as part of the Roach Digital Backend (RDBE).

All of the HSA stations are equipped with instrumentation compatible with the VLBA observing capabilities. The highest recording rate on the VLBA (4096 Mbps) can be requested for the HSA, excluding Arecibo.

VLBA and HSA constraints

There are several constraints when using or collaborating with the VLBA or the HSA networks that need to be considered:

- Proposals requiring significant additional correlator resources, such as multiple phase centres per field or multiple pulsar phase bins, should consider mechanisms to support the correlation without adversely affecting the throughput of other projects. These should be entered in the technical justification section of the proposal.
- There are strong constraints on GBT time availability coming from non-open skies time and VLA time is highly oversubscribed, so their participation needs to be properly justified.

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ANNEX 1.5: The VLA as a VLBI station

Figure 9. Jansky Very Large Array (VLA)

The phased-VLA [RD16] can be included in VLBI networks, VLBA, HSA or Global VLBI as a single element. In phased array mode it offers the equivalent sensitivity, including sampling losses, of a single 115-m antenna. A well phased VLA, with all 27 antennas, when added to the 10 antennas of the VLBA, improves the sensitivity in a naturally-weighted image by a factor of about 2.4. Baselines between the phased array and any VLBA antenna should be about 4.6 times more sensitive than baselines between any two VLBA antennas. The addition of the VLA also provides one shorter baseline (Y27-PT) than the VLBA which may be valuable for larger sources.

VLBI proposals which request the GBT or VLA (or any other HSA telescope) as elements of the VLBI array do not need separate proposals---those telescopes can be selected as separate VLBI stations from a VLBA/HSA NRAO proposal using the PST tool.

All VLA phased array observations are fixed date. Phased array observations need to be scheduled using the SCHED program. The program called vex2opt converts the VEX file into files that can be read in by the VLA Observation Preparation Tool (OPT). Vex2opt is run by NRAO staff once the schedule is submitted. The OPT generates the observing script for the VLA.

After observation completion the observer receives by email logs from the VLA operator and the VLBA operator.

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VLA brief technical description as VLBI component

The VLA supports standard VLBI observations at frequencies of 1.7, 3.0, 5.0, 8.4, 15, 22, 33, and 43 GHz. The VLA records up to 2 Gbps to a Mark5C recorder (maximum bandwidth 256MHz per polarisation).

The real-time autophasing TelCal application runs at the VLA during the observations deriving the delay & phase corrections for each antenna/polarization/subband. The antenna signals are then corrected in the correlator, summed up, re-quantized to 2-bits, and finally recorded in VDIF format on the Mark5C recorder at the VLA site. Autophasing is performed in appropriate calibrators or targets and solutions are applied to the target/s.

A VLA VLBI observation also produces standard VLA visibility data (standard WIDAR), so the user will probably want to do standard VLA flux calibration, and other calibration required to use the VLA data by itself.

VLA constraints

When preparing VLA schedule files, the following facts and guidelines should be noted:

- Only 27 antenna phased array mode is allowed. For situations where the observer may only want the inner antennas for the phased sum, this can be handled as a comment to the operator. Single dish is only offered as part of the VLBA Resident Shared Risk Observing program.
- The user should allow a scan of about 1 minute for phasing. TelCal does not determine the correction until the end of a scan. Subsequent scans can apply the stored corrections, e.g. on a target which is too weak to determine the correction. Phasing imposes some restrictions on the subbands setups and how phasing is transfer between scans.
- Autophasing should be done on a calibrator which is a point source to the VLA's synthesized beam and, if transferring phases to a target, close to the target. The strength required depends on the frequency, weather and elevation. A good rule of thumb is >100 mJy for 1-12 GHz and >350 mJy for 12-45 GHz. Higher flux densities are required for low elevations particularly at high frequencies.
- Autophase corrections are valid for a duration that depends on the VLA array configuration, observing band, weather, elevation and, e.g., activity level of the sun. Recommendation to be conservative because an observation that does not contain frequent enough autophasing cannot be fixed in post-processing for the VLBI data, and sensitivity will be lost. Very broad rules of thumb for frequency of determining and applying new autophase corrections are:

  – C & D config: 20-30 minutes at low frequencies; 10-20 minutes at high frequencies
  – A & B config: 5-10 minutes at low frequencies; 2-5 minutes at high frequencies. May want to avoid observing at 45 GHz in these configurations, also because of the very small synthesized beams.

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- Strong radio frequency interference (rfi) can make it impossible to autophase, so pick your subbands to avoid rfi.
- The observer should follow the VLA general observing restrictions and advice, such as the one minute setup scan for each correlator configuration (i.e. band) at the beginning of the observation and the amount of overhead needed for reference pointing at the start of an observation, scans no longer than 10 minutes,
- No pulse calibration system is available at the VLA. If you plan to use more than one subband, then you should observe a strong and compact source to serve as a manual pulse calibrator; see the VLBA Observational Status Summary.
- Targets positions accurate to a *VLA synthesized beam* (rather than the much larger primary beam) must be used for phased-array observations.
- At frequencies higher than 15 GHz reference pointing for the VLA should be used.
- To derive source flux densities and/or produce images from the standard VLA data, then the VLA observe file should include at least one scan of a primary flux density calibrator for the VLA.
- The VLA slews at a slower rate than the VLBA.

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ANNEX 1.6: ALMA as a VLBI station

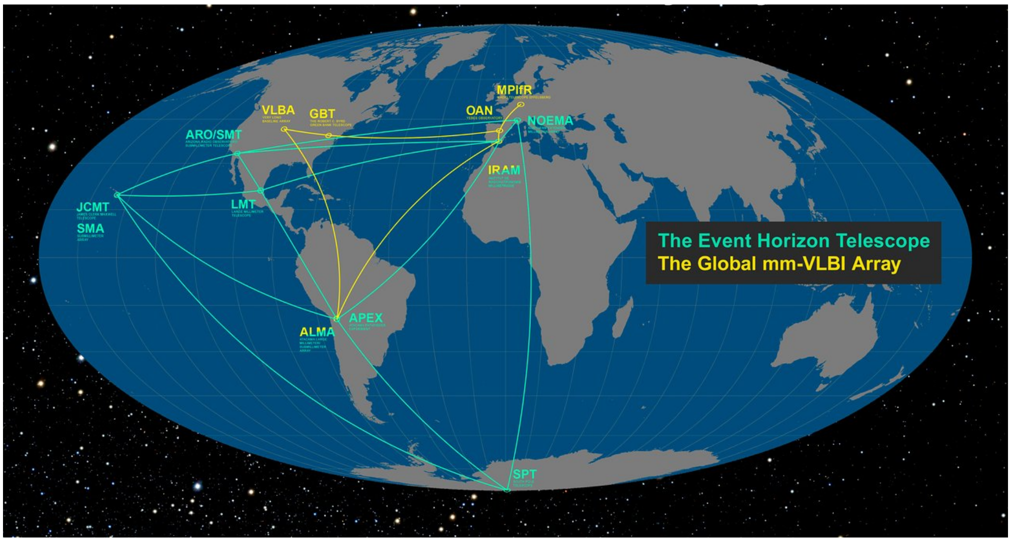

Figure 10. The ALMA Interferometer as part of VLBI networks

Similarly to the VLA case, ALMA [RD17] can be phased arrayed to participate in VLBI observations at high frequencies together with the Global-mm VLBI Array (GMVA) and the Event Horizon Telescope (EHT). The ALMA example is included in this study as it may have similarities with the SKA-VLBI case.

The Global 3mm VLBI Array (GMVA) offers 3-4 times more sensitivity and a factor of 2 higher angular resolution than the stand-alone VLBA or the HSA. It consists of 8 VLBA antennas equipped with 3mm receivers, the 100m GBT, the IRAM 30m telescope on Pico Veleta (Spain), the phased NOEMA interferometer on Plateau de Bure (France), the MPIfR 100m radio telescope in Effelsberg (Germany), the OSO 20m radio telescope at Onsala (Sweden), the 14m telescope in Metsähovi (Finland), and the OAN 40m telescope in Yebes (Spain). In addition, telescopes of the Korean VLBI Network (KVN), the Greenland Telescope (GLT) and the Large Millimeter Telescope (LMT) could be requested as part of the GMVA. The GMVA usually observes just 2 weeks per year, one week in spring and another in autumn. The actual duration of each session depends on proposal pressure and ranges between 2 and 5 days. Correlation is performed at the MPIfR VLBI correlator in Bonn. The GMVA network sticks to the NRAO access regulations.

The Event Horizon Telescope (EHT) is a 1.3 mm VLBI array whose primary goal is to observe and image nearby supermassive black holes with sufficient angular resolution to resolve the hot material just outside the black hole event horizon. The EHT network currently consists of

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telescopes in the USA (Arizona and Hawaii), Mexico, Chile, Spain, Greenland, and the South Pole that together provide a resolution of better than 30 microarcseconds. To provide the sensitivity required to observe sources at such fine detail, EHT partners have developed ultrawide-bandwidth instrumentation and correlation facilities capable of handling very high data rates. The maximum bandwidth that can be output from the ALMA phasing system is 7.5 GHz.

VLBI proposals should include a quantitative justification as to why ALMA is essential for the goals of the project. For 3 mm VLBI observations, PIs must have submitted a proposal to the GMVA network by the NRAO 1 February deadline in addition to their ALMA VLBI proposal for the mid-April deadline*.* Both ALMA and the GMVA VLBI network review and rank the 3mm VLBI Proposals independently, and both must accept a given proposal for the observations to be scheduled. *For* 1-mm VLBI, the ALMA Observatory will forward the submitted 1-mm VLBI proposals to the EHT Consortium network for technical assessment. A merged list of acceptable proposals will be made by the ALMA science advisory committee. Thus, proposers do not need to send their proposal to the EHTC.

VLBI observations will be conducted using a “campaign mode”, whereby specific dates are reserved for the execution of VLBI programmes in coordination with the other facilities in the VLBI network and so that VLBI experts are available to help with programme execution.

ALMA brief technical description

- The ALMA phased sum used for VLBI may be constructed only from those that lie within a circle of radius 0.5 km.
- ALMA passive (phasing on calibrators) and direct (phasing on target) phasing modes are available.
- Default GMVA 3mm observing mode of 4 Gbps, dual polarization. The KVN will not be available in this mode. Only VLBA telescopes will be available at 7mm in this mode.

ALMA constraints

VLBI observing windows will be identified during the periods when the 12-m Array is in one of the three most compact configurations (maximum baselines less than 500 m).

Direct phasing of the ALMA array is limited to targets with a correlated flux density >0.5 Jy contained within an unresolved core on ALMA baselines up to 1 km (in Band 3 and 6). Direct phasing on the science target ("active" phasing) thus puts a lower limit on the brightness of the science target.

- For weaker sources, the option of "passive" phasing has been recently introduced. In this mode, the ALMA array is periodically phased on a bright calibrator close in angular distance

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to the science target. There are thus no restrictions on the flux density of science targets using passive phasing (aside from SNR considerations on VLBI baselines). The properties of the phasing calibrator must meet the same criteria as for actively phased observations, and it is recommended that the phasing calibrator (S > 500 mJy) lie within an angular separation of no more than 5 degrees from the science target. Proposers must specify the phasing calibrator in their proposal;

- Only proposals for continuum observations in Bands 3 and 6 will be accepted. These will be obtained in full polarization using the high spectral resolution (FDM) mode and the 64-input Correlator.
- In order to make a clean linear-to-circular polarization transformation of ALMA recordings, any target source must be observed for a duration of at least 3 hours (breaks for calibrators permitted) to sample a range of parallactic angles.
- Large Programs (>50 hours of observing time) are not permitted because phased ALMA is a non-standard mode. No long-term programs may be proposed, and no proposals will be carried over into the next cycle.
- There is a cap for VLBI observing time on each ALMA Cycle of (e.g. 5% for Cycle 7).
- The proposers are required to enter a VLBI total time requested. Here, they should enter the amount of time requested for ALMA (and not the total time requested to the GMVA/EHTC networks, which may be longer). Note that this time must include overheads. For ALMA + GMVA or EHTC the total observing time (including overheads and ALMA calibrations) is a factor of four (25% duty cycle) of the expected time on source.
- A VLBI session will not exceed one week. Therefore, if multi-epoch observations are requested, they must fit within one week and the total time must be the aggregate time of all observations.
- In publications using ALMA data, the use of the ALMA and its resources should be acknowledged.

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ANNEX 1.7: The NRAO-GBO/XMM-Newton coordinated multi-frequency observations

Figure 11. XMM-Newton, ESA.

In recognition of the importance of multifrequency studies for a wide variety of science targets, NASA has stablished Joint Programs between its Large Observatories, e.g. HST, Chandra, NRAO, etc. Recently XMM-Newton telescope signed a reciprocal and cooperative arrangement for coordinated observations with NRAO and GBO facilities [RD10], and well as with other NASA, European and International facilities. A 20% of the total XMM proposals are currently asking for time within the joint programs.

Specifically, for the XMM agreement with NRAO-GBO Observatories, proposals may be submitted to one of the facilities to request time on both the radio and X-ray observatories. The time is awarded only for highly ranked proposals that require the use of both observatories and does not apply to usage of archival data. The XMM-Newton Project may award up to 3% of NRAO/GBO/LBO open skies observing time. Similarly, the NRAO/GBO/LBO Time Allocation Committee may award up to 150 ks of XMM-Newton time per year.

Proposers should take special care to justify both the scientific and technical reasons for requesting observing time on both facilities. It is not essential that the requested radio and

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X-ray observations be simultaneous, however clear discussion of the required level of coordination is essential for evaluating feasibility. No observations, requiring simultaneous observation with both facilities, with a reaction time of less than 2 working days from an unknown triggering date will be considered for this cooperative program. It is the responsibility of the PI to inform both observatories immediately if the trigger criterion is fulfilled.

Both observatories reserve the right to reject any approved observation that is in conflict with safety or mission assurance priorities or schedule constraints, or is otherwise deemed to be non-feasible.

Apart from the above, both missions' general policies and procedures currently in force for the final selection of the proposals, the allocation of observing time, the execution of the observations, data rights and publication agreements remain unchanged.

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ANNEX 2: SKA Operational Plan

The following sections are paragraphs extracted from the SKA Operational Plan document [RD03] that apply to SKA-VLBI. Each paragraph has a comment (in blue font) outlining issues or explaining the implications. The structure of Annex 2 is the same as for the SKA Operational Plan document, but some sections have been omitted as are not relevant for our purpose.

As a reference, the complete document is available here: https://astronomers.skatelescope.org/wp-content/uploads/2014/02/SKA-TEL-SKO-0000307_01_OCD-part-1-signed.pdf

ANNEX 2.1: SKA Objectives and Key Performance Indicators

ANNEX 2.1.1: Delivery of transformational science

The SKA Project shall be designed to be capable of transformational science, with a combination of sensitivity, angular resolution and survey speed far surpassing current state-of-the-art instruments at relevant radio frequencies. SKA-VLBI Comment: VLBI will definitely contribute to the transformational science with its superior resolving power.

Principle 8: The primary success metric for the SKA Observatory will be the significance of its role in making fundamental scientific discoveries and facilitating overall scientific progress, expressed as high impact, peer-reviewed scientific papers using SKA data. SKA-VLBI Comment: This coincides with usual VLBI success metrics. Will SKA and the VLBI networks share the success metrics?

A vigorous SKA Observatory Development Programme (SODP) will be implemented. This programme will provide the Observatory with the designs of upgrades to existing capabilities and new capabilities, commensurate with the evolving ambitions of the SKA user community. The SODP will be described in the SKA Development Plan (priority between science operations and development). SKA-VLBI Comment: VLBI development included also here? As VLBI is an observing mode of the SKA Observatory in principle yes. VLBI development will need to be coordinated with the VLBI networks, for compatibility. SKA-VLBI may use this opportunity to enhance the VLBI capability (e.g. more beams, etc.), although regular upgrades to the VLBI terminal (h/w and s/w) would be part of normal support of the VLBI capability.

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ANNEX 2.1.2: Scientific success metrics

Anticipated use of commensal observing, in which multiple science projects can be carried out simultaneously. SKA-VLBI Comment: VLBI observing mode is compatible with all types of SKA commensal observing subjected to availability of resources.

Scientific success metrics: over-subscription, number of publications and citations per unit cost. SKA-VLBI Comment: This is compatible with VLBI metrics. Will VLBI metrics influence SKA metrics? e.g. in case of no VLBI proposals?

These metrics can be analysed with different amounts of granularity SKA-VLBI Comment: e.g. for VLBI projects in particular.

ANNEX 2.1.3: Operational success metrics

Operational success metrics: highly efficient observatory (faults, unavailability of computational resources, planned maintenance, operational availability and of specific capabilities, etc.) SKA-VLBI Comment: these metrics could be complemented by the EVN median absolute error in gain calibration or other VLBI networks indicators. VLBI equipment and capability availability could impact these metrics. Responsibility of the VLBI Consortium in this respect (or any other group/s responsible for the VLBI equipment) needs to be clearly established.

ANNEX 2.1.4: Accountability and Reporting

The annual reports submitted by the Director-General, and the papers provided to the Council for its meetings, will report on progress against the objectives of the Observatory. A set of key performance indicators, as described in the previous sections, will be developed and reported to enable monitoring and oversight of the Observatory's performance. SKA-VLBI Comment: Any responsibility from VLBI networks in preparation of annual reports for the SKA Council?

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ANNEX 2.2: Constraints and Assumptions

ANNEX 2.2.1: Operating Constraints

Hosting agreements

The SKA Observatory will consist of the following physical infrastructure components:

- a Global Headquarters (GHQ) situated at Jodrell Bank, UK;
- SKA1-LOW, an array of dipole antennas at the Murchison Radio Observatory in Western Australia; and
- SKA1-MID, an array of dishes in the Karoo region of South Africa.

In addition, there will be establishments elsewhere in Australia and South Africa that will provide scientific and technical support for SKA1 operations. SKA-VLBI Comment: VLBI equipment will be located at Science Processing Centres, SPCs, located in Perth and Cape Town.

Activities and obligations in the UK, Australia and South Africa will be constrained by and subject to Hosting Agreements with these three countries. These Agreements are currently being negotiated. SKA-VLBI Comment: details for VLBI support at the SPC facilities need to be included in the Hosting Agreements with Australia and South Africa.

Operations Policy

An Operations Policy has been negotiated by the Members as a Tier-2 document under the Observatory Convention. This policy will, when agreed and approved, specify the functional structure of the Observatory from the perspective of telescope operations. SKA-VLBI Comment: To include coordination details between SPCs and VLBI networks

At the time of writing, discussions are ongoing between the Office and the Host Countries to develop a new operational model. SKA-VLBI Comment: Any outcomes for VLBI?

Access Policy

An Access Policy has been negotiated by the Members as a Tier-2 document under the Observatory Convention. This policy will, when approved by the Observatory Council, constitute a governing document for the operation of SKA1.

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The elements of the **SKA Access Policy** that are salient for this document are as follows:

- Access will be proportional to Members' shares in the project, as determined by their financial contributions. SKA-VLBI Comment: VLBI networks are open sky, available to worldwide users.
- Subject to the preceding constraint, Access will be based on scientific merit and technical feasibility, evaluated through a common time allocation process. SKA-VLBI Comment: Compatible with VLBI TA Processes? Different TAC interactions?
- Time will be made available for Key Science Projects (§6.4.1), PI projects, Director-General's Discretionary Time and Open Time, at proportions to be determined by the Council's overall scientific strategy for the Observatory. SKA-VLBI Comment: SKA VLBI observing mode will be available for all types of SKA projects, as any other observing mode.
- The Director-General will be responsible for time allocation, advised by a Time Allocation Committee (TAC).
- Science data products are to be made openly available after a suitable proprietary period as determined by the Council. SKA-VLBI Comment: Compatible with VLBI periods?
- Associate Members will be treated in the same way as Members for the purposes of Access. Thus throughout this document, reference to "Members" should be interpreted as "Members and Associate Members".
- All science data products will be owned by the SKA Observatory. SKA-VLBI Comment: does this apply to VLBI data as well?

The detailed implementation of the Access Policy is being developed in a Tier-3 document, the Access Rules and Regulations. SKA-VLBI Comment: Any outcomes for VLBI?

Safety, Health and Environment

We shall integrate good Health, Safety & Environmental performance as a core element in every planning, design, construction and operation activity to achieve our aim of being safe and secure. This includes improving the wellbeing of all involved in the project work by addressing our impact on climate change and waste, preventing pollution, enhancing biodiversity and encouraging inclusion and healthy living during the design and construction phases and beyond.

To this effect, the SKAO will issue an HSE policy statement and associated management plans. An SKA Project Safety Management Plan has been published, an SKA Project Environmental Plan is being drafted. Compliance with the SKAO's HSE policy and mandatory plans will be required for all SKAO staff and its agents, contractors and visitors. SKA-VLBI Comment: VLBI to comply with SKA HSE policy and management plans.

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Radio-Quiet environment

The SKA1 Telescopes will be located within radio-quiet zones in Australia and South Africa. These zones are globally unique resources. Both countries have obligations through the Hosting Agreements to protect the sites from radio-frequency interference arising from external influences within their jurisdiction and from other facilities on the sites. The SKAO will be responsible for controlling self-interference arising from the operation and maintenance of the SKA telescopes, and for limiting radio pollution of the sites that may affect other facilities. SKA-VLBI Comment: VLBI equipment is located at the SPCs in Perth and Cape Town, with no RFI impact on the telescopes' sites.

Data Flow

One of the unique challenges of the SKA is its extremely high data rate: it is currently estimated that each SKA telescope will produce 300 PB of science data each year in routine operations. SKA-VLBI Comment: VLBI will contribute to the data flow, but in principle not significantly, apart from projects that request SKA complementary imaging with maximum spectral resolution, for spectral line studies.

No provision was made for the distribution of data to users, nor for computational facilities to enable users to undertake further data analysis, both of which are mission-critical if the SKA is to deliver on its scientific promise. The SKA Board determined that these functions should be provided by a set of SKA Regional Centres (SRCs).

SRCs are to be funded and operated by the regions in which they reside, and they are therefore not formally within scope of the project: the relationship between the SKAO and the SRCs is to be collaborative in nature, based on Memoranda of Understanding and an accreditation framework. SKA-VLBI Comment: The relationship with VLBI networks could also be based on MoUs, independently with each VLBI network and/or under a global umbrella.

The SKA Regional Centres are envisaged as a global collaborative network of high-performance computing facilities that will provide SKA users with access to data products for visualisation, analysis and further processing. SRCs will provide core functions to the Observatory and the SKA user community, but are also expected to differ from region to region in additional functions that they may choose to provide, based on their individual and specific business cases. SKA-VLBI Comment: will there be SRCs specialized in VLBI? What type of support will be needed at the SRCs for VLBI? This is something being discussed by the SRC Steering Committee with support from the SKA Science Working Groups.

Development and implementation of the SRC concept is the responsibility of the SRC Steering Committee. SKA-VLBI Comment: VLBI networks implication and participation? VLBI

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SWG? For the purposes of this Plan, it is assumed that an ensemble of SRCs will be put in place as currently envisaged.

From Operations Concept Document (OCD) rev 3:

The Observatory will deliver data products to the SRCs from each SDP, managed in order to control usage on the long-haul links. SKA-VLBI Comment: VLBI may also use these links, to send the data to the VLBI correlators, that in some cases may be collocated with some SRCs, so a schedule for usage of this resource will be needed.

Individual SRCs may subscribe in advance, or be pre-allocated as part of the TAC process, to receive data products from specific projects in order to plan for efficient use of each SRC. SKA-VLBI Comment: VLBI could use SRCs collocated with SPCs and VLBI correlators (e.g. Pawsey supercomputing centre at Perth).

Advanced Data Products (ADPs) that are deemed worthy of publication by the PI, or that have been published, will be added to the SKA science archive and made available to all users (while respecting all appropriate proprietary access periods). SKA-VLBI Comment: To define ADPs for VLBI. Are proprietary periods compatible with VLBI periods?

ANNEX 2.2.2: High-level Assumptions

High-level assumptions that have been made in the development of this Plan are listed in Table 1. These assumptions are distinct from design choices, which are presented in the following chapters.

Table 1: High-level assumptions.

No.	Assumption	Ref.
A1	SKA Phase 1 will be delivered, in compliance with the SKA1 Construction Proposal.	N/A
A2	An ensemble of SRCs will be provided by the SKA Members, in compliance with governance arrangements and technical interfaces to be determined.	4.1.6
A3	The SKA Telescopes will be capable of 24-hour operation. SKA-VLBI Comment: VLBI support 24h for e-VLBI operations? To take into account correlators' staff availability. For example, EVN correlator staff is not usually available on weekends but this could be arranged if necessary for the projects.	5.3
A4	The proprietary period will be 1 year from the date of notification to the user that data products are available. SKA-VLBI Comment: does it need to be the same as VLBI proprietary periods? Data products released to the users from the VLBI correlator and from SKA will happen at different times. Does data release need to be coordinated?	5.3.1
A5	It Is assumed, for the current version of this Plan, that the Design Baseline will be implemented. Adoption of the Deployment Baseline will affect the resource requirements, and potentially also the observing modes to be made available. These	5.3.2.2, 9

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	impacts will be evaluated when the Deployment Baseline is defined as part of construction planning. SKA-VLBI Comment: anticipate that VLBI observing mode may be delayed in the deployment baseline.	
A6	A global VLBI consortium will be established. SKA-VLBI Comment: Is this really needed for the SKA VLBI capability? The VLBI equipment is not part of the SKA budget, it needs to be provided externally, currently it is assumed to be provided by a global VLBI consortium. SKA may have individual agreements with the VLBI networks and/or with a global VLBI consortium specific for VLBI with SKA.	5.3.2.9
A7	The existing working patterns for the precursor telescopes ASKAP and MeerKAT will be adopted. Routine, on-site operational support will be provided on a 5-day working week.	5.6.2
A8	The SOCs, SPCs and EOCs will be delivered by the Host Countries in compliance with SKA requirements. SKA-VLBI Comment: To include VLBI requirements for the SPCs.	6

ANNEX 2.3: Observatory Operations

ANNEX 2.3.1: Principles of Operation as an Observatory

On 25th July 2013, the SKA Board approved a set of top-level operational principles. These principles were amended slightly on 29th October 2013, and then more substantially on 14th July 2016 to reflect the ongoing evolution of the operational concept.

These principles govern the design of SKA operations. It is anticipated that they will be superseded by the Operations Policy and the Access Policy.

The SKA Observatory

No.	Principle	Ref.
1	The SKA Observatory will consist of SKA Telescopes[2], local activities necessary for their operation, data processing and archive facilities and a Global Headquarters. SKA-VLBI Comment: Is the VLBI equipment part of SKA although provided by an external entity?	6
2	The SKA Observatory will be operated as a single organisation.	7
3	The purpose of the SKA Observatory will be to enable scientists to pursue world- leading scientific programmes, to organise and conduct improvements and upgrades of the SKA telescopes in order to provide and maintain facilities that are at the forefront of science and technology and to ensure the protection of the SKA sites for the SKA and future radio telescopes. SKA-VLBI Comment: Need to inform, coordinate upgrades with the VLBI networks, e.g. correlator Beamformer upgrade, data format, etc.	3
4	The scope of the SKA Observatory will be to provide, commission, operate, maintain, and	5

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	upgrade the SKA Telescopes, and to produce scientifically-viable data products from the telescopes. SKA-VLBI Comment: what about the VLBI terminal? Currently it is assumed that a VLBI consortium will provide, maintain and upgrade the VLBI terminal, and SKA will operate it. What about VLBI data? Is there any responsibility from the VLBI networks in this respect?	
5	The SKA Telescopes will be located within radio-quiet zones provided by the Host Countries of South and Southern Africa and Australia. SKA-VLBI Comment: VLBI equipment to be located at SPCs without impact.	N/A
6	The expected lifetime of the SKA Observatory is 50 years. SKA-VLBI Comment: VLBI agreements for 50 years? MoU? Best effort basis?	8.4
7	The SKA Observatory will be the technical design authority for the SKA Telescopes. SKA-VLBI Comment: VLBI Consortium to support VLBI technical design.	7
8	The primary success metric for the SKA Observatory will be the significance of its role in making fundamental scientific discoveries and facilitating overall scientific progress, expressed as high impact, peer-reviewed scientific papers using SKA data. SKA-VLBI Comment: Does it coincide with VLBI success metrics? Will they share success metrics?	3
9	(deleted)	N/A

Structure of the SKA Observatory

10	The SKA Observatory shall be led by a Director-General, who will report to the SKA Observatory Council. SKA-VLBI Comment: VLBI responsibility to contribute to annual report? Will the SKA DG be part of the VLBI board of directors? Will the SKA be a member of the VLBI networks?	7
11	The SKA Observatory shall operate a Global Headquarters (GHQ), which will have overall responsibility for the SKA Observatory.	6
12	The SKA Observatory shall establish a presence in the two Host Countries for the purpose of controlling SKA infrastructure and conducting SKA Operations in the Host Countries.	6
13	The SKA Observatory shall appoint an external body to provide independent advice to the Director-General on the planning and conduct of SKA operations and science. The members will be appointed on the basis of their scientific expertise and experience.[3] SKA-VLBI Comment: External body with VLBI networks representation or VLBI expertise?	3.4
14	The SKA Observatory Council will control the SKA brand and the GHQ will implement policies on such branding. SKA-VLBI Comment: VLBI networks to respect SKA brand and acknowledge SKA participation, and the other way around, to coordinate media communications between VLBI networks and SKA Observatory.	N/A

SKA Operations

15	SKA Operations is the sum of all SKA activities that are centrally managed, and which are neither part of the SKA Construction Project[4], nor Planning Activities[5]. For this purpose, managed activities include those contracted out, provided in kind by agreement, or similar. SKA-VLBI Comment: Can VLBI be considered in kind by agreement? The VLBI equipment is provided externally.	5
16	The Host Countries will have an obligation to protect the radio-quiet zones for the SKA and future telescopes from outside transmissions and other telescopes on site to agreed standards. The SKA Observatory will have responsibility for control of self-interference from SKA Telescopes.	4.1.5
17	The SKA Observatory Council will define an SKA Access Policy governing the right to propose for observations and to have access to data. SKA-VLBI Comment: To include VLBI policies.	4.1.3
18	The Director-General will retain the final authority for time allocation, within the policy	4.1.3

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	framework set by the Council. SKA-VLBI Comment: To be specified in the VLBI MoUs.	
19	The SKA Observatory will be designed to accommodate a mix of large co-ordinated observations proposed by large teams and PI-driven programmes. SKA-VLBI Comment: VLBI is an observing mode of the SKA observatory that can be used to support any type of programme.	5.2
20	The SKA Observatory will calibrate SKA data and make science data products and ancillary data products available to the users. SKA-VLBI Comment: is there any responsibility for VLBI networks on data containing SKA data? Level of compromise with VLBI users is different.	0
21	The SKA Observatory will coordinate a network of SKA Regional Centres that will provide the data access, data analysis, data archive and user support interfaces with the user community.	4.1.6
22	(deleted)	N/A

ANNEX 2.3.2: Science Programmes

The SKA will undertake science observations that enable generation of science data products in accordance with the Access Policy.

Scientific Scope

A wide range of scientific programmes that utilise the capabilities of the SKA have been identified that would lead to fundamental advances in our understanding of the cosmos, list of high-priority science goals (indicative only, since the scientific landscape within which the SKA will operate continues to evolve and diversify), SKA-VLBI Comment: several high-priority science goals will be enhanced by VLBI.

Requirements Scope

Observing time requirements on the two SKA telescopes as well as high performance computing (HPC) requirements to generate the associated Observatory Data Products. SKA-VLBI Comment: VLBI observing time and HPC requirements (real-time beamforming and Imaging) depend on individual VLBI projects. Requirements for HPC are not very demanding for VLBI projects.

The programmes requiring the largest observing time allocations will be classified as Key Science Projects (KSPs), while those with smaller time allocation needs will be classified as Principal Investigator (PI) projects. SKA-VLBI Comment: VLBI observing mode available for both.

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Coordinated programmes relying on both LOW and MID

Together such programmes may account for about 50% of the observing time that would be needed to undertake the objectives identified in that process. SKA-VLBI Comment: For VLBI at least 2 science cases need simultaneous observations with both telescopes, and several science cases will use broadband observing using MID and LOW (not necessarily simultaneously).

ANNEX 2.3.3: Science Operations

World's largest observatory in cm and m wavelength range, surpassing in sensitivity, field of view and survey speed. Operate 24h every day, flexible observing programme to face adverse circumstances: SKA-VLBI Comment: good for VLBI, SKA flexibility appropriate to adapt to the VLBI observing programmes. SKA flexibility is very well suited to VLBI observing.

And multiplex observing programmes as much as possible. SKA-VLBI Comment: Compatible with VLBI. This poses an advantage for VLBI, as it will allow more opportunities to observe using VLBI mode, limited by available resources.

Access to data and resources

Access to the SKA Observatory and its resources shall be guided by the Access Policy and the Access Rules and Regulations (currently being developed).

Basic principles:

- time allocation shall be a fair process driven by the scientific excellence of proposals and will be robust against, and be able to resolve, conflicts of interest wherever they may arise; SKA-VLBI Comment: VLBI proposals to compete on same terms. In principle there is no need to allocate fixed time for VLBI for each observing cycle as SKA scheduling is flexible. The number of VLBI projects for each cycle will not surpass the VLBI networks annual availability. VLBI and SKA observing cycles may not coincide.
- the priority for the time allocation process is to ensure that the science programme of the SKA is of the highest quality, undertaking high-impact science projects; SKA-VLBI Comment: VLBI projects need to be observed on certain dates. SKA to make sure that higher priority projects than the VLBI projects are also observed during the cycle. Anticipate that VLBI may ultimately impact this priority due to scheduling constraints affecting the other higher priority projects.

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- access will be proportional to Members' contributions to the SKA Observatory. SKA-VLBI Comment: VLBI is open skies. VLBI operational mode available for all SKA users.

For the SKA Observatory, allocation of "telescope time" and resources to provide Observatory Data Products (ODP). As such, proposals will need to justify not only their telescope time but also their use of other resources, especially the computing resources of the SDP and SKA Regional Centres. SKA-VLBI Comment: VLBI proposals to specify telescope time and resources needed. VLBI needs SDP and SRC resources as well as a data network link to the VLBI correlator centres.

ODPs are property of the SKAO. SKA-VLBI Comment: What about VLBI data? What about SKA ODPs from VLBI observations (e.g. simultaneous SKA Imaging)?

Proprietary period of 1 year (Assumption), after publicly available, DG to alter period: SKA-VLBI Comment: Most VLBI networks have the same proprietary period (except the LBA which is 18 months). How do we make imaging products available with VLBI visibilities? SRCs? Should they store both? At VLBI networks? Periods are different. Altered period is compatible and/or needs to be coordinated with VLBI networks?

Advanced data products normally generated at SRCs: SKA-VLBI Comment: is there any for VLBI? To be defined by SRC Steering Committee and VLBI SWG.

Observing

Scans, Scheduling Blocks and Observing Blocks.

Definition of Scan. data continuously acquire, subarray (or array) configuration fixed during the scan, SKA-VLBI Comment: same definition as for VLBI.
Definition of SB. Contains all information needed to observe and obtain ODPs, i.e., telescope, instrument, correlator and SDP configurations. They execute on a subarray. SBs may have a range of durations and may be executed many times. SKA-VLBI Comment: For VLBI the SBs contain fixed times. Execution can be halted but they cannot be reinitiated, execution needs to jump to the current observing time. SB are equivalent to Field System snp and prc files together.
OB containers of SBs that are necessary to achieve the science goals of the project, e.g. SBs with very specific scheduling constraints SKA-VLBI Comment: e.g. to be used for VLBI with cadence observations (parallax signature, variability, etc.).
SB generated from content of a submitted proposal, amended using the Observation Design Tool, SKA-VLBI Comment: for VLBI SB generated from VEX files as well, proposal will have complimentary information (e.g. for e-VLBI, this info could be the destination IPs of the VLBI correlator).

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Each science programme associated to an OB (a proposal may have different science programmes?). Each observation is a single SB. SKA-VLBI Comment: e.g. for cadence VLBI observations, one OB containing all the SBs at correct observing times.

Observing Modes.

A number of observing modes will be commissioned and supported by the SKA to enable the scientific goals of the Observatory and its community to be realised. These observing modes can be differentiated between imaging and non-imaging modes. The observing modes shall be:

- Imaging
- Pulsar Search
- Pulsar Timing
- Dynamic Spectrum
- Transient Search
- Very-Long Baseline Interferometry (VLBI)
- Calibration

All observing modes can be executed simultaneously in a subarray. SKA-VLBI Comment: subject to limited resources for MID. True always for LOW.

Independently of the observing modes, there are different ways in which the telescope carries out observations, i.e., tracking modes (§5.3.2.2.3). Furthermore, there will be special observing modes in place to allow fast reaction to Targets of Opportunity, triggered events, etc.

- **Imaging modes** (continuum imaging -including a fast imaging pipeline- and spectral line or Zoom window imaging, for both modes is provided correlated visibilities and auto-correlations, and all 4 Stokes imaging),

- **non-imaging modes** (pulsar and transient search, pulsar timing, flow-through, dynamic spectrum, VLBI, transient buffer)

VLBI mode: This mode provides independently steerable tied-array beams to participate in VLBI imaging and non-imaging observations, with other radio astronomy observatories located around the globe. This mode provides ultra-sensitive elements (at µJy noise level) to the VLBI networks, at milli-arcsecond angular resolutions. At least four dual-polarisation VLBI beams can be formed from one or more subarrays, including up to the full array (FOR MID only). Polarisation corrected and RFI masked tied-array beam voltage data is recorded in

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VDIF format compatible with external VLBI correlators, for inclusion in either real-time (e-VLBI) or post-observation correlation.

For SKA1-LOW, VLBI beams can be formed with a maximum bandwidth of 256 MHz per polarisation, per beam. For SKA1-MID, visibility data are produced simultaneously within each VLBI-mode subarray to provide calibration solutions to establish beam coherence and to enable standard imaging with the subarray in interferometric mode. SKA-VLBI Comment: visibility data is produced for both telescopes, for LOW without any restriction.

The standard VLBI bandwidths are available up to 200 MHz per polarisation, per beam-channel. For increased bandwidth, the appropriate number of VLBI beams should be configured with the same pointing. SKA-VLBI Comment: do not really need to specify this, just comment total maximum bandwidth per VLBI beam is 5 GHz.

Telescope Tracking modes.

Sidereal, non-sidereal, wide area scanning and drift scanning. SKA-VLBI Comment: Tracking modes for VLBI are sidereal and non-sidereal

Targets of Opportunity, triggered events and overrides.

The ability to acquire new objects quickly, in response to alerts that have been triggered by events either externally or internally to the SKA (e.g., Targets of Opportunity (ToOs), transients, etc.), is an important science driver for the SKA. SKA-VLBI Comment: VLBI proposals can be regular, ToO or triggered.

VOEvent protocol, SKA-VLBI Comment: compatible with VLBI networks? Do VLBI networks plan to use it? for e-VLBI?

Existing ToO projects, scientific ranking assigned in advance by a TAC, pre-defined SB, SKA-VLBI Comment: VLBI has pre-existing approved projects for triggered projects. Late binding info to SBs, VLBI Comment: applies to VLBI proposals as well.

Projects that may result in trigger events will need to include rules for issuing VOEvents. SKA-VLBI Comment: To include VOEvents rules in the VLBI proposals that may trigger events.

The TAC may wish to recommend override status, immediately abort or stop the currently executing SBs at the end of the current scan (1sec latency). SKA-VLBI Comment: implications

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for VLBI? Stop the VLBI observation or pause if VLBI observation is long enough. Need to inform the VLBI networks.

Decisions on which SBs to abort will be based on their scientific priority and the amount of resource that will be freed. SKA-VLBI Comment: for VLBI projects take into account that it uses other observatories' resources and if SKA is completely necessary for the observation.

VO alerts may also be received as requests from researchers in the community. As there is no existing project, that request for observing will go directly to the Director-General, or their delegate in the Observatory (12h latency). SKA-VLBI Comment: Same model as for VLBI, but with different latency (several days), to adjust to the slowest latency.

Calibration.

Array calibrations. SKA-VLBI Comment: For VLBI need to include antenna/station coordinates (or subarray phase centres) determination with respect to TRF.

Real-time calibration for complex gain, polarisation leakage, for beamformers. Plus gain monitoring, SKA-VLBI Comment: beamforming process for VLBI (calibrator & target cycle and constraints) to be determined during commissioning. Real-time DD corrections for low frequencies for off-axis beamforming. For SKA complementary Imaging, alternatives to use a calibrator model or the SKA local sky model.

The Observatory will maintain an ongoing calibration programme that will periodically undertake routine calibration observations at various cadences. At the time of writing, the details of and policies for this calibration programme are as yet undefined.

Timing conventions.

SKA UTC timescale, timing constraints in UTC, local sidereal time or local time. SKA-VLBI Comment: Compatible with VLBI usage of UTC.

Apply leap seconds automatically or manually, Implementing the leap second shall not interrupt SKA Operations, observe across leap seconds but never start observing. SKA-VLBI Comment: VDIF specs require that the VDIF seconds field encode all seconds including leap seconds since the reference epoch (which is defined in UTC). Same restrictions for VLBI with respect to the start time on leap second?

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Commensal Observing Scans.

Commensal observing will have a significant impact on the scientific productivity of the SKA. Three different types of commensal observing are defined: Data commensality (multiple projects use same observatory data products), observing commensality (same field with different observatory products) and multiplexed commensality (use of subarrays). Decisions on commensal projects will be taken at the cycle planning and observation planning stages. SKA-VLBI Comment: VLBI is compatible with all types of SKA commensal observing, limited by resources.

At the proposal submission or observation design stage, it is not possible to know with absolute certainty whether a particular project can be executed commensally or not, and as such PIs are not required to identify or label their proposals or projects as commensal. SKA-VLBI Comment: VLBI does not need to specify commensality in proposals but can identify it. Advantage for commensal VLBI projects with lower scheduling priorities (VLBI is either scheduled or not).

Subarrays.

Subarray is a subdivision of an SKA telescope that can be scheduled and operated independently of other subarrays, maximum number of subarrays is resource limited. Engineering and astronomy (end-to-end capability) subarrays. Subarrays templates. Dependent and independent subarrays. SKA-VLBI Comment: VLBI compatible with use of subarrays and templates specific for VLBI typical configurations (core, but variable size, several core subarrays, just one antenna or station for outrigger components, etc.) and dependent and independent subarrays. Engineering subarrays for testing and commissioning. VLBI projects will also need simultaneous observing modes for each subarray.

Resources are schedulable entities. SKA-VLBI Comment: VLBI will need several schedulable resources, e.g. SKA external data link.

Tied-array beams.

Same or different subarrays (up to whole array for Mid), configured and operated independently, different pointings on the sky. Need real-time calibration for beamforming (minimise efficiency losses caused by misaligned signal phases due to electronics or atmospheric effects and polarisation impurity, as well as state-of-the-art RFI detection and excision algorithms). SKA-VLBI Comment: Applies to VLBI (on scan boundaries). The scan duration is the same for all tied-array beams in a subarray.

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VLBI.

VLBI projects will be allocated through the SKA's normal proposal review process, as Coordinated Proposals. Furthermore, by the time SKA1 becomes operational it is anticipated that proposals to use the SKA as part of a VLBI network may also be peer-reviewed for scientific merit and assessed for technical feasibility by a separate body as part of procedures that are yet to be established. At the time of writing discussions of this separate body, which will have a global perspective, are in their infancy. The SKA Director-General will determine how the SKA Observatory will be represented in this body, which will need to establish a policy with the SKA with regard to data rights. SKA-VLBI Comment: Individual MoUs with the VLBI networks are also compatible with this model for VLBI observations.

A VLBI observing project will contain the necessary timing constraints as to when the observation needs to be executed with other stations in the VLBI network. The PI initially generates a standard VLBI VEX (VLBI Experiment) file, which is common for all the observatories participating in the VLBI observing and contains a complete description of the observation and the participating observatories, including:

- observatory characteristics (e.g. geographical coordinates, wrap limits, etc.);
- target and calibrator information (e.g. coordinates, flux density, etc.);
- technical information about the observation design (e.g. type of VLBI data acquisition terminal, bandwidth, channels, etc.); and,
- the detailed observing schedule specifying the observing and calibration scan times in UTC.

This VEX file will be attached to the SKA VLBI observing project submitted to the observatory, ingested and parsed to extract the necessary technical details needed to generate the associated SBs. The original VEX file will remain associated with the SB so that it is accessible by the Observation Design Tool. Users will be able to amend their observing details by submitting an updated VEX file (e.g., change of calibrator) up to a few hours before the observation starts, an action that will automatically update the associated SB accordingly.

The global VLBI Consortium will be responsible for providing the VLBI Element for the SKA Observatory, that will operate in standard record/playback mode or in e-VLBI mode (streaming of VLBI data to the external correlator, for real-time correlation). The VLBI Element (a.k.a. VLBI Terminal) will be integrated in the SKA Observatory for Monitor and Control functions using the Tango framework. SKA-VLBI Comment: Is this considered in kind contribution? VLBI needs to support SKA during construction and operations phases as well.

From OCD:

Table 10: Operational requirements (VLBI)

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SKA1-OPS	SKA1-SYS_REQ	Requirement
18	3138	SKA1_Mid VLBI data shall conform to the SKA-VLBI ICD (to be written).
	3610	SKA1_Low VLBI data shall conform to the SKA-VLBI ICD (to be written).
81	NEW	On command, SKA1_Low and SKA1_Mid shall configure to support VLBI observing as a constituent member of a Global VLBI network.
82	NEW	On command, SKA1_Low and SKA1_Mid shall configure to support VLBI observing in standard mode (record/playback) or in e-VLBI mode.
83	NEW	SKA1_Low and SKA1_Mid shall monitor and control the VLBI Element.
84	NEW	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.
85	NEW	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.

Custom Experiments.

Extension of existing SKA functionality or performance by the addition of hardware or software, Custom experiments will be subject to the same review process as other PI proposals. The custom experiment team are responsible for conforming to existing SKA interfaces and will provide, and test, any additional hardware and software necessary for the success of the experiment. Any team proposing a custom experiment will be responsible for providing data products (not raw data) suitable for archiving, and abide by the same proprietary period policy as other SKA data. This requirement to archive data products will be waived only in exceptional circumstances. SKA-VLBI Comment: Any responsibility from VLBI with respect to data and calibration?

Time accounting.

The execution time to observe scheduling blocks, including the time to slew and/or acquire an object, and perform calibrations shall define the time charged to projects. Due to commensality and subarrays, the total chargeable and execution time can be greater than 24 hours as there will be more than one project being executed at the same time. SKA-VLBI

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Comment: Weather impact and faults? Giving time back to VLBI projects will require coordination with the VLBI network for the next observing session. For VLBI usually observing time cannot be added from different observing dates, the whole observation will have to be repeated, with the same total observing time.

Observatory Operations - Phase 1

Telescope time is conventionally awarded to PIs via a two-phase process. In Phase 1, the proposal is prepared and submitted by a PI and their Co-Is, followed by a peer review process undertaken by an independent TAC. This review includes a detailed technical description of the observations proposed. If the proposal is successful, it enters Phase 2 as a project where scheduling blocks are generated and technical details can be refined (perhaps following feedback, recommendations or restrictions from the TAC). PIs will, through a common, central utility, be able to prepare and edit draft proposals, and to track their active and past projects. SKA-VLBI Comment: VLBI PIs to use both VLBI network and SKA processes. This depends on Global VLBI consortium decision and/or individual agreements with VLBI networks.

KSP (large programmes) and PI, SKA-VLBI Comment: both can use VLBI observing mode

The system is designed to implement the terms of the Access Policy; the detailed implementation rules are in the draft Access Rules and Regulations (currently being developed).

Proposal Preparation and Submission.

Usage of a Proposal Handling Tool.

The basic constituents of a proposal include an abstract, scientific and technical justifications, data product pipeline requirements, the total integration estimated using a sensitivity calculator, calibration needs, and access to astronomical databases to resolve names of specific objects and/or their coordinates. An estimate of the resources required at SKA Regional Centres will also be needed. To aid in the design of observations, the PI shall be able to access a library of standard template configurations. SKA-VLBI Comment: For VLBI proposals include the coordinated facilities. VEX file will be provided later (whenever project approved plus info like correlator IPs, etc.). Compatible with templates. Anything else? Letter from VLBI network approving the project? It depends, may delay VLBI network scheduling.

If the science goals of a proposal require the use of both LOW and MID, then it will be possible to request and justify the use of both telescopes within a single proposal. A

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technical section for each telescope will need to be included with the proposal. SKA-VLBI Comment: applies to 2 SKA-VLBI science cases.

From OCD: SKA Sensitivity Calculator. SKA-VLBI Comment: To include SKA-VLBI performance

Proposal Types.

Any potential user of the SKA will be able to apply for a variety of proposal types. The main categories of proposal are:

- Standard proposal (PI);
- Key science Project (KSP);
- Open time (OT): there will be a TBD fraction of time available to PIs from non-member countries
- Director-General Discretionary Time (DDT): DDT proposals can be submitted at any time needing only the approval of the Director-General;

  SKA-VLBI Comment: all types of proposals to include possibility to observe in VLBI mode.

Following subcategories of proposal:

- Target of Opportunity (ToO);
- Long-term proposal (LT): these are for projects that require more than one proposal cycle to complete (e.g., long-term monitoring campaigns) but are too short in overall observing time to qualify as a KSP;
- Joint SKA Proposal (JSP): a proposal that requires both LOW and MID telescopes to achieve the science goals; o such proposals may be linked so that observations can be executed contemporaneously; SKA-VLBI Comment: 2 SKA-VLBI science cases
- Coordinated proposal (CP): a proposal requiring observing to be coordinated with another facility (either ground- or space-based) with user-specified scheduling constraints provided. SKA-VLBI Comment: VLBI proposals are coordinated proposals, need to specify coordinated facility/ies.

Proposal Review and Time Allocation.

The time allocation process will be managed and supported from the GHQ.

Time allocation process will be split along defined science themes, with separate panels reviewing proposals submitted in each theme. SKA-VLBI Comment: VLBI proposals have different science themes. To use the different SKA panels for reviewing VLBI proposals depending on their science theme.

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All submitted proposals should be technically feasible.

From OCD: TAC to assess scientific merit. Provide a numerical grade on the scientific justification for those proposals. SKA-VLBI Comment: Compatible with the different VLBI networks numerical grades?

Grades assigned to proposals will require normalisation so that direct comparisons can be made across the thematic boundaries. SKA-VLBI Comment: Share normalisation rules with VLBI TAC?

The TAC will be able to use a cycle planning tool to assess how the proposals they are recommending for awards of telescope time are distributed across the sky, with oversubscription, ability to identify commensality between different projects, how observing time is being distributed amongst the Members, explore different strategies to craft the best possible science programme for the Observatory for each observing cycle. VLBI Comment: Tool to include VLBI proposals statistics in comparison with other projects. SKA observing cycles and calls for proposals compatible with VLBI?

SKA-VLBI Comment: VLBI proposals with SKA to be sent to all relevant TACs, joint decision? different VLBI networks observing cycles do not coincide and SKA observing cycles may not coincide either (proposal submission different dates, it may happen SKA proposal already approved when VLBI network already not aware about it).

Proposal Lifecycle and States.

Proposal Under Review: the proposal is currently in the process of being reviewed and assessed. SKA-VLBI Comment: Joint process with VLBI TACs? Assign a reviewer accepted by SKA and VLBI networks? Review may happen at different times than other SKA proposals.

Reviewer invitation sent: a reviewer for a proposal has been identified and an invitation has been sent requesting their assistance in reviewing the proposal within a given timeframe. SKA-VLBI Comment: Reviewers from a pool of approved by members and VLBI networks? What to do for a coordinated proposal with another facility?

Note that at the time of writing the Time Allocation policy has not been written and the role of “reviewers” is not defined. SKA-VLBI Comment: Is this policy available now?

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Observatory Operations - Phase 2

Successful proposals that have been allocated and approved time and resources, on the SKA Observatory and SKA Regional Centres, become projects. Containers for all pertinent information related to them including: scheduling blocks, observing logs, quality assessment (QA) records, project progress against allocation, associated calibrations, faults encountered and the environmental conditions during observations, record of all communications to and from the PI and the SKA observatory regarding the project. SKA-VLBI Comment: For VLBI projects include the VEX file, any additional info like correlator IP, etc. projects containers to include metadata and logs after the observation completion.

Observation Design.

Scheduling Blocks are initially generated by automatically extracting the relevant technical details from the original proposal. SKA-VLBI Comment: And from the VEX file for VLBI projects.

The PI will also be able to specify how the data will be processed by selecting the data reduction pipeline(s) that will be associated with the observed data. SKA-VLBI Comment: Pipelines for VLBI (VLBI visibilities or not, etc.).

PIs will carry out the majority of the observation design for their projects during proposal preparation with help from support staff. SKA community become familiar with SKA science operations, including the observation preparation and design tools. SKA-VLBI Comment: User support for VLBI projects? Need knowledge of VLBI networks.

The sooner they do, the sooner their SBs will be considered in observing plans for execution. Observation design of projects will be possible throughout the observing cycle. SKA-VLBI Comment: For VLBI projects observing dates are decided in advance so no advantage. SKA observing cycle needs to be compatible with VLBI cycles.

Observation Planning.

SBs contained in the Observation Data Archive (ODA).

Observation planning for each telescope can then be executed considering all known constraints: maintenance and commissioning schedule, simultaneous SKA1 or other facility observations (VLBI!), target visibility, etc. SKA-VLBI Comment: VLBI imposes constraints on observing date and times. Many projects need certain cadence (parallax and variability), some are time critical. VLBI project to include resources needed: subarray configuration with

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minimum number of antennas needed, etc. It needs to inform the maintenance and commissioning schedule.

The scheduling priorities of SBs that emerge from observation planning are driven by the scientific priority assigned by the time allocation process, based on the expected environmental and resource constraints. SKA-VLBI Comment: VLBI project to be scheduled at certain date and time, it does not have scheduling priorities. Make sure enough SKA resources are available for that date (subarrays with enough antennas, a-priori calibration, stable subarray phase centre, etc.).

Identifying Commensality.

Commensality between SBs of different or the same projects will need to be identified during the observation planning stage. SKA-VLBI Comment: It is not responsibility of the VLBI PI to identify commensality.

A Compound SB is a scheduling construct that contains a set of SBs to be executed in parallel on a defined set of compatible subarrays within the context of a single project. SKA-VLBI Comment: VLBI will need compound SBs as it will use different subarrays in many cases (several bands observations, a subarray for each outrigger antenna, etc.)

The scheduling priority of the commensal group of SBs in the compound SB will be determined by the highest-ranked SB in that group. SKA-VLBI Comment: VLBI does not have or need a scheduling priority. This only affects the commensal SBs executed with the VLBI observation.

Flexible Observing, Scheduling and Execution.

Dynamic scheduling: This is a mode of operation that allows the observatory to react quickly and efficiently to changing environmental conditions, availability of resources and capabilities, and other operational or scientific needs. SKA-VLBI Comment: Advantage for VLBI to be able to include ToO VLBI projects at very last moment or for e-VLBI projects to change observing plans in real-time (e.g. e-EVN automatically triggered projects will update the SB in real-time). VLBI projects schedule needs to inform the maintenance schedule.

For flexible observing an automated decision is made at the “point of execution”.

Flexible observing decisions are informed by: SKA-VLBI Comment: For VLBI, the resources would need to be checked in advanced, in case the VLBI terminal is not available (or other required real-time resources) therefore the observation needs to be cancelled, the VLBI network notified, and dynamically substitute by another project, without impacting SKA observing efficiency. If SKA was completely necessary for the success of the VLBI

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observation, it will have to be rescheduled during the next VLBI observing cycle (coordinating with VLBI network).

- dish/station availability;
- availability of receiver bands and observing modes;
- data transport capacity;
- compute availability in the correlator and beamformer;
- processing capacity of the Pulsar Search and Timing engines;
- ingest and processing capacity of the SDP;
- capacity of the VLBI buffer;
- observability of the target(s);
- environmental constraints (wind speed, ionosphere, RFI, etc.), and SKA-VLBI Comment: Any for VLBI? Some constraints anticipated a priori.
- scheduling priorities of the SBs.

Flexible scheduling will also allow the Observatory to quickly respond to internal or external triggers and events and change the observing schedule depending on the priority and urgency of the triggered event. SKA-VLBI Comment: For VLBI ToO usually several days response time is needed, unless the network is already observing a VLBI or e-VLBI project (this project needs to have override status for another VLBI project), that immediate reaction is possible.

At the time of writing, a detailed policy governing the implementation of ToO and VO Events is TBD. SKA-VLBI Comment: Is it ready now?

Manual Operation and Control.

The SKA1_Mid and SKA1_Low shall provide the capability for authorised personnel to take manual control of the telescope, its subarrays, components and instrumentation.

- by manually editing the execution schedule to insert an automated operation at a future point in time (by either sending an SB or engineering operation for execution);

SKA-VLBI Comment: For e-VLBI it may be advantageous to change the SB in real-time if required. Needs communication between the VLBI correlation centre and SKA Operations.

SKA-VLBI Comment: e-VLBI needs remote access from VLBI correlator staff to the VLBI terminal, to change the IP of the network destination if required and stop data xfer in case of problems.

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Science Data Products

Pipelines and Data Products.

Science data products with QA will be generated by the SDP. Only those products required for the project(s) requested with a specific SB will be produced. SDP's pipelines will be tuned to the specific requirements of each SB to deliver the required calibration solutions and ODPs (Observatory Data Product). SKA-VLBI Comment: VLBI may need many of the ODPs together with the beam voltage beams. To be specified for each VLBI project.

Quality Assessment.

QA occurs within each element of the observatory that undertakes data processing (SDP - real-time and off-line processing pipelines-, CSP -PSS and PST-, LFAA MCCS -station calibration-). SKA-VLBI Comment: For VLBI SDP and MCCS relevant (what about CSP beamformers?).

SDP QA purpose is to check whether the observations are proceeding or have proceeded as planned. In the real-time case, QA can give useful feedback that might affect whether the current SB should be continued or aborted (e.g., the impact of the ionosphere on the data), and in the off-line case measure the performance of the telescope system and determine whether the SDP pipelines themselves are appropriately tuned. SKA-VLBI Comment: For VLBI both SDP QA will be used, but no need to abort observation due to RFI, ionosphere, etc., just if mentioned in the project (to include in VLBI project rules for QA to abort real-time observing).

Lifecycle of Data Products.

Observatory data products, i.e., those generated within each SDP, will be delivered to SKA Regional Centres where users will access them. SKA-VLBI Comment: VLBI users will need to access data products from SRCs.

SDP hot and cold buffer. Deletion of unprocessed data from the cold buffer is also possible, and might be required if the buffer has insufficient space to take in data from a ToO observation that has been triggered with override status. SKA-VLBI Comment: This may affect VLBI projects (just to SDP data, unless VLBI buffer is also needed), stop data transfer to SRCs?

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In addition to being delivered to SRCs, all ODPs will be stored in a long-term preservation system for both telescopes. it will be faster and better to copy missing products from another SRC than to use the observatory's copy.

Once delivered to the SRCs, users will be able to access these data products, if they have appropriate permissions. SKA-VLBI Comment: VLBI users with access.

As products move out of their proprietary periods (if applicable), user access will be opened up to the general public. SKA-VLBI Comment: Proprietary periods compatible with VLBI? They may differ.

From OCD: Advanced data products generated within the SRCs will inherit the data access rules of the products that go into making them, though the details of this are still TBD. SKA-VLBI Comment: ADPs for VLBI? To be defined by VLBI SWG and SRC steering committee.

Science Operations Workflow

Issue of a Call for Proposals, SKA-VLBI Comment: compatible with VLBI? Can a VLBI PI send a proposal to a VLBI network asking for SKA when the SKA Call of proposals is closed? Or the opposite?

The likely operating model is for scheduling priorities to be updated on a regular basis, e.g., every 2–3 days (TBD), informed with the most up-to-date information from across both SKA telescopes. SKA-VLBI Comment: advantage for VLBI, to add VLBI observations on short timescales (for ToO, etc.).

Note that for the SKA, data reduction is an integral part of the observing workflow. If the SDP ingest is not available for any length of time, data acquisition will also cease and observations will need to be repeated. SKA-VLBI Comment: Scheduling a VLBI observation occurs well in advance, therefore SDP resources can also be planned well in advance. SDP resources for VLBI are required for real-time calibration and imaging from the same SKA subarray or the whole SKA array. To repeat a VLBI observation requires the coordination of the whole network.

The Operator may decide to continue or repeat the SB depending on the severity of the problem encountered. SKA-VLBI Comment: For VLBI SBs cannot be repeated, and need to be executed at a fixed time. VLBI project to specify under what circumstances the observation should be cancelled (severe weather conditions like wind, snow, etc.), subject to SKA safety rules.

Submit a ticket describing the fault for future investigation. The link to this ticket is automatically added to the Shift Log. SKA-VLBI Comment: Will the VLBI correlator have

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access to tickets related to VLBI observations? Via the VLBI project (only access by the PI). Will SKA use the VLBI means to communicate problems? For example, the EVN uses the following feedback pages http://old.evlbi.org/session/feedback.html. SKA-VLBI Comment: Will SKA conform to the e.g. EVN Permanent Actions items?

SKA Regional Centres

The Observatory will develop a standard set of workflows and pipelines that can be used by the community to generate ADPs. These workflows will be deployed on and be available across the global SRC network for all astronomers to use on their SKA data. SKA-VLBI Comment: Specific tools for VLBI data: gravitational lenses analysis, calibrator polarisation characterisation, etc.

ANNEX 2.3.4: Engineering Operations

Availability

An SKA telescope is defined to be operationally capable when it can perform astronomical observations, including signal processing and data reduction, with at least 95% of its collecting area. SKA-VLBI Comment: Study what this means for VLBI, outrigger antennas can be substituted by operational and similar characteristic ones (use templates), for the core this means losing about 10 antennas for MID! How much is that for a 4km core? To check with the sensitivity VLBI calculator, it also depends on subarrays defined (10 antennas for half a core is a lot, e.g. 10 antennas from 64 MeerKAT antennas is 15.6 %). VLBI proposals or templates to specify minimums.

The SKA1_Mid and SKA1_Low shall each have an operational availability of at least 95%. SKA-VLBI Comment: Does this also apply to the VLBI terminal? To define responsibilities.

Maintenance Strategy

Detailed maintenance plan, encompassing both hardware and software components, will be developed as part of the system design. SKA-VLBI Comment: Maintenance of VLBI terminal at SPC? Hosting agreements, VLBI correlator staff at SPCs?

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The maintenance plan will include both preventive maintenance and corrective maintenance, varying from system to system, depending on the known failure modes. SKA-VLBI Comment: To define maintenance of the VLBI terminal.

All on-site telescope systems must be designed to make maximal use of Line Replaceable Units (LRUs). SKA-VLBI Comment: VLBI equipment located at SPCs. VLBI terminal FlexBuff recorders design is based on LRUs (hot swap replaceable hard disks).

An inventory of working spares must therefore be maintained. SKA-VLBI Comment: Same for SPC VLBI equipment?

It is not envisaged that the entire array will be taken down for maintenance; SKA-VLBI Comment: VLBI schedule to inform maintenance schedule, dates and resources needed.

Failure Detection and Identification

Telescope health monitoring fault detection and diagnostic performance shall enable compliance within the operational availability down time constraints. In event of a failure, the objective is for telescope health monitoring to automatically identify the fault to the level of the LRU for repair of the telescope. SKA-VLBI Comment: VLBI terminal will use SKA Tango for monitor and control, including health monitoring.

The monitor and control systems will permit deep interrogation of sensor values, and will enable remote identification of faults down to LRU level so that maintenance and repair activities can be planned and carried out efficiently. SKA-VLBI Comment: Detail of the VLBI parameters to be checked still to be determined.

Maintenance Management

Maintenance management software: Work orders will be created for all repair and scheduled maintenance activities, SKA-VLBI Comment: does this also apply to equipment in SPC? Who will be responsible for maintenance at SPCs?

OEM repair activities and Service Level Agreements (SLAs) will be managed by the support personnel. Regular maintenance work orders/job cards will automatically be sent to the OEM or Service Provider to notify them of the requirements. SKA-VLBI Comment: VLBI repair by OEM (Original Equipment Manufacturer, VLBI consortium), does this mean VLBI will receive work orders? How?

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Engineering Management System

The Engineering Management System (EMS) will consist of software to support engineering and maintenance functions for both telescopes (including PRTS). SKA-VLBI Comment: VLBI to be included in this system.

All problems identified during the construction and operational phases will be reported, logged and tracked by means of the operational Problem Reporting and Tracking System (PRTS – §7.16), as a measure to effectively assign and track problem resolution. SKA-VLBI Comment: Tickets to be attached to the VLBI projects.

Software Support

From OCD: The telescopes shall have the capability to remotely update and roll-back software versions as may be required. SKA-VLBI Comment: VLBI terminal also capable.

Configuration Management

Configuration management will be maintained throughout the operational phase and will consist of data relating to the telescopes, infrastructure and support equipment. SKA-VLBI Comment: VLBI equipment under configuration management?

All configuration changes will be managed and traced through the operational life cycle by means of an Engineering Change Proposal process. SKA-VLBI Comment: This means that any change to VLBI terminal is subjected to an ECP process?

Technical Data and Publications

Technical publications will be developed to provide sufficient information for personnel to perform specific tasks for operation and maintenance. It shall be based on international best practice and shall complement training material development. SKA-VLBI Comment: Provide VLBI equipment with documentation.

Product Breakdown Structure. This structure will define the locations and positions for all maintenance items; also referred to as slot-positions in a maintenance structure. The locations structure will contain all hardware and software items down to the required maintenance level. SKA-VLBI Comment: VLBI (h/w and s/w) to be included in the PBS.

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Technical publication information will be managed and developed to provide Interactive Electronic Technical Manuals/Publications (IETM/P). The data modules, in xml format, will be the prime source for the IETM/P. SKA-VLBI Comment: VLBI to comply with these standards?

Supply Support

Initial spares and consumables stock (including any strategic spares requirements) shall be delivered and confirmed in place at the allocated storage locations, at commencement of telescope commissioning. Relevant consumables or spares stocks consumed during commissioning shall be replenished / restored to operational stores before conclusion of the commissioning activity. SKA-VLBI Comment: VLBI spares at SPC.

The number of spare parts & consumables required will be calculated during the LSA (Logistic Support Analysis) and by simulation/modelling. Supply support stock level shall be assigned, based on at least an 85% probability of spare in stock when required. SKA-VLBI Comment: Implications for VLBI?

The LRUs and Shop Replaceable Units (SRUs) shall be packaged, handled, stored and transported as described in the SKAO Preparation, Preservation, Packaging, Handling, Storage and Transport requirements (to be written), as identified during the Logistic Support Analysis. SKA-VLBI Comment: To write this for VLBI LRUs and SRUs.

I-level, O-level and D-level maintenance facilities with different levels of spares. SKA-VLBI Comment: Will VLBI use this? Mostly the VLBI correlator.

The accountability of all items and consumables will be controlled using Item Orders and Delivery Notes transaction logs. The electronic signatures on receive and dispatch notices will ensure item accountability. SKA-VLBI Comment: VLBI equipment as well. Purchase orders by VLBI consortium or VLBI networks.

Obsolescence Management

The telescope design and support baselines will be continuously assessed for obsolescence-sensitive items and obsolescence risk. SKA-VLBI Comment: Responsibility for VLBI consortium or VLBI networks for technology refreshes?

From OCD: Technological refresh strategies will be accounted for in the system architecture design and selection of technologies, products and vendors. SKA-VLBI Comment: For VLBI as well?

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Personnel Considerations

The maintainer is a technical person that is skilled and qualified and has received appropriate technical training. The maintainer will be responsible for corrective and preventive maintenance. SKA-VLBI Comment: VLBI terminal to be maintained locally by SPC staff (or local VLBI correlator staff) or remotely by VLBI correlator staff.

Support and Test Equipment

The Support & Test Equipment (S&TE) requirements for the various maintenance levels are to be determined during the LSA process. SKA-VLBI Comment: Any for VLBI?

From OCD: Observatory Operating Life

The Observatory is expected to operate for 50 years. Maintenance, replacements, refresh and retro-fit programmes must be identified to achieve this expectation. These programmes will focus on obsolescence risk mitigation and the changing requirements within the astronomy community. SKA-VLBI Comment: Define VLBI support expected during the SKA Operating Life.

From OCD: Constraints

Rigorous implementation of the Safety, Health and Environment policy for all activities on the remote sites; and protection of the radio-quiet environments of the remote sites. SKA-VLBI Comment: This does not apply to VLBI as its equipment will be placed at SPCs. VLBI will have to comply with SPCs regulations.

All on-site systems be engineered to fail to a safe state in the event of loss of power or communications. SKA-VLBI Comment: This does not apply to VLBI located at SPC, to comply with SPC requirements.

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From OCD: Standards

Common standards should be employed to the maximum possible extent. Such standards will be approved for implementation by the SKA Office and will be specified in the Level-1 requirements. SKA-VLBI Comment: Is this already in L1 requirements? What standards apply to VLBI at SPCs?

From OCD: Acceptance

For both telescopes, components will be handed over from the construction project to observatory operations incrementally in a series of roll-outs. Each handover will involve an acceptance review, in which compliance with the operational requirements will be assessed. Although a full set of acceptance criteria has not yet been developed, a documentation set covering maintenance requirements will certainly be included. SKA-VLBI Comment: Acceptance for VLBI?

From OCD: Remote Support

Software and firmware maintenance will be performed remotely and tested off-line, where possible. This includes planned updates and upgrades as well as unplanned maintenance. SKA-VLBI Comment: This is compatible with VLBI software and firmware maintenance from VLBI correlator (consortium?).

ANNEX 2.3.5: Problem Reporting and Tracking

All problems identified during the construction and operational phases will be reported, logged and tracked by means of the operational Problem Reporting and Tracking System (PRTS – §5.4.5) as a measure to effectively assign and track problem resolution. SKA-VLBI Comment: Tickets attached to the VLBI project, SKA operator (or friend of the project, described later) to notify VLBI network? To use VLBI problem reporting systems, as e.g. the EVN feedback pages? http://old.evlbi.org/session/feedback.html

Notify appropriate personnel of the faults. SKA-VLBI Comment: To notify VLBI network.

Assign domain specialists to investigate issue. SKA-VLBI Comment: To take into account VLBI consortium resources, correlator staff, etc?

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ANNEX 2.3.6: Working on Site

Presence on telescopes sites

Throughout the design phase of the project, a guiding principle has been to minimise the number of operational staff working on the sites to maintain the SKA Telescopes. This is motivated by two factors:

- it is anticipated that the most significant source of RFI on the sites will arise from human activity; and
- both telescope sites present hazardous environmental conditions.

SKA-VLBI Comment: VLBI equipment to be installed at SPCs. Already included in the design provision to send the VLBI beam data from the CSP to the SPCs.

ANNEX 2.3.7: Interaction with the user community

User Support

Support for SKA users will be provided by a mixture of local and regional offices (including but not limited to SRCs) and resourced separately from the SKA Observatory. SKA-VLBI Comment: Institutions like JIVE could give SKA user support for VLBI projects.

The SRC network will be the primary access portal for users to access all information pertinent to their proposals and projects, including access to their data and processing platforms. This 'SKA Science Gateway' will be accessible from the web pages of the SRCs, or from the SKA home page. SKA-VLBI Comment: VLBI networks or Consortium part of the SRC network?

Helpdesk facility managed by SKAO GHQ. From OCD: Requirements for a Helpdesk facility, and how it will interface with the SKA Observatory, SRCs and local/regional offices, will be defined. SKA-VLBI Comment: Any requirements from VLBI community?

The SKAO GHQ will assess all tickets and ensure that they are assigned to appropriate owners, who may be situated in any of the three Observatory sites. Of course, at times, the expert solution may reside within the community, and the Observatory will reach out to those individuals for assistance. SKA-VLBI Comment: With support from VLBI correlator staff for VLBI projects, Consortium, VLBI SWG, etc.

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"Friend of Project" (FoP). The FoP will serve as the point of contact for PIs and Co-Is to raise project-specific queries. Queries on specific projects that generate tickets via the Helpdesk system should alert the FoP automatically. SKA-VLBI Comment: FoP for VLBI project to have support from VLBI correlator staff, Consortium, VLBI SWG, etc.

Advisory Committees

SKA Users Committee and SRC Users Committee. SKA-VLBI Comment: With VLBI representation.

In addition to these, the SKA Observatory Council will establish a Science and Engineering Advisory Committee (SEAC), SKA-VLBI Comment: with VLBI knowledge.

SKA Users Meetings

The Observatory will organise a major SKA meeting every two years (TBD) that will be open to scientists, engineers, and policy-makers from across the whole SKA community and beyond. SKA-VLBI Comment: VLBI Networks/Consortium role? VLBI community to participate

Publications and Dissemination

The SKA Observatory will disseminate news, information and events that are of relevance and interest to the SKA Observatory, its community and stakeholders. Additionally, the Observatory will provide support to the user community in communicating their research to a broad audience: SKA websites, social media, electronic newsletters, annual reports, etc. SKA-VLBI Comment: VLBI networks/consortium role? Reports? Coordinate efforts (joint press releases, etc.).

In addition, the SKA Observatory will: engage with members of the public through regular public talks to disseminate its research; conduct educational workshops wherever appropriate; and provide teacher resources and lesson plans based on its research to the teacher community. SKA-VLBI Comment: Any support from VLBI?

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ANNEX 2.4: Observatory Functional Structure

Functional structure of the SKA Observatory. SKA-VLBI Comment: VLBI network/consortium to interact with GHQ and SPC in particular (or SOC?)?.

a high level of communication is absolutely essential. Barriers to communications and mutual understanding will be reduced by:

- investing in high-capacity telepresence capabilities between all the major locations; and
- implementing a regular programme of personnel exchanges and visits.

SKA-VLBI Comment: Implications for VLBI network/consortium: budget for visits, participate in telecons, invest in telepresence capabilities?

A list of the functions to be carried out by the Observatory, and the allocation of those functions to the GHQ and the two Telescopes, is presented in Table 5:

Business- Enabling Functions: Long-term policy: SKA-VLBI Comment: VLBI policies with each network and as Global

Observatory Operations: SKA-VLBI Comment: missing an Interface to VLBI networks and other potential coordinated facilities.

ANNEX 2.5: Observatory Lifecycle

Construction Phase. Starts at T0. SKA-VLBI Comment: What is expected from VLBI? Baseline design vs. deployment baseline? No VLBI capability? But have VLBI to give support to construction? Improve interfaces, support commissioning plan and SRC development, support to SPC commissioning, etc?

Transition to Operations. Demonstrate the ability of the Observatory to execute a selected set of day-1 observing modes, from proposal preparation through to data delivery. Operations Acceptance Review, marking the handover from construction to operations. SKA-VLBI Comment: Any support from VLBI?

Operations Phase. additional observing modes will need to be commissioned, and software development will continue on an essentially continuous basis. SKA-VLBI Comment: VLBI support.

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Obsolence and upgrades. The expected lifetime of the SKA Observatory is 50 years, Accordingly, the Level-1 requirements to which the telescopes are being designed do not specify a 50-year lifetime. SKA-VLBI Comment: VLBI support to Phase 1.

Obsolescence management is therefore key to their operational support. SKA-VLBI Comment: Support from VLBI?

The SODP will provide for the continuous development of new techniques and technologies for the SKA. SKA-VLBI Comment: VLBI role?

Decommissioning. Decommissioning and site restoration is the final phase of the SKA Project. SKA-VLBI Comment: VLBI responsibilities? Retire VLBI equipment? Recycle?

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