# Report on SKA-VLBI Key Science Projects

JUMPING JIVE

Project ID: 730884

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# 1 Executive Summary

As a concluding act of the JUMPING JIVE WP10 “VLBI with the SKA”, a workshop was organized in 2019 at the SKA headquarters, to bring together SKA specialists with VLBI experts (Fig. 1). Until then, the first and only standalone VLBI meeting related to the SKA was organized in 2001, 18 years before, in Bonn. At that time, the SKA concept was not fully developed, but it was widely agreed that it would be a high-angular resolution instrument. In the following years, the picture of a more compact and wide-field of view survey instrument started emerging. The science topics that require high spatial resolution were therefore not prominent when the science priorities were defined for the phase-1 SKA telescopes. Intriguingly, it was realized that some of the highest-ranked high priority science objectives (HPSOs, Braun et al. 2014, RD001) may crucially depend on high spatial resolution observations. At the same time, the community recognized that there is a cost-effective way of realizing this. The idea was to include the multi-beam phased-array SKA1 telescopes in VLBI networks – the concept of SKA-VLBI was born (Paragi et al. 2015, RD002). This marked the start of reviving the SKA VLBI Focus Group (now a full- Science Working Group) activities, and the organization of VLBI parallel sessions at major SKA conferences, to discuss the science.

It was however clear that sporadic meetings and occasional/heroic efforts of some individuals will not be sufficient to make progress. This is why WP10 came to life within the JUMPING JIVE project, to facilitate and promote SKA-VLBI. During the project WP10 has produced 4 key deliverables (including the present document):

- D10.1 Details on VLBI Interfaces to SKA Consortia
- D10.2 Operational Model for inclusion of SKA in Global VLBI
- D10.3 Portfolio of SKA-VLBI Science Cases
- D10.4 Report on SKA-VLBI Key Science Projects (this document)

Major project highlights are related to these deliverables. D10.1 was recognized by the SKA Organization as an official SKA document. It played an important role in the approval of the System-Level Critical Design Review in December 2019, in the approval of the Construction Proposal, and, together with the D10.2 operational model, in the approval of the Observatory Establishment and Delivery Plan in September 2020.

The other two, D10.3 and D10.4 had a role in activating the community to start brainstorming on future VLBI Key Science Projects with the SKA. But they had additional, and somewhat surprising outcomes in that they made a significant impact on the design of the SKA1 telescopes. The possible science use cases in D10.3 made us revise how these can be mapped to the design capabilities of the SKA1 telescopes. During the 2019 KSP workshop we further clarified these cases and made concrete proposals to the SKAO on how to implement them (see Sections 5-6, and Annexes 3-4). Most importantly, the SKA has approved the Engineering Change Proposal (ECP) initiated by us. This ECP proposed to implement the large number of

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VLBI beams allowed by the design, to facilitate ultra-high precision (down to 1 microarcsecond) astrometry SKA-VLBI projects. This was an outstanding milestone for our project.

It was a great pleasure for us to see some of the 2001 Bonn workshop organizers and participants meeting with the new SKA generation at our workshop. As the construction of the SKA1 telescopes starts on 1 July 2021, both generation's dreams will come true.


**Figure 1. SKA-VLBI workshop poster**

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# 2 Introduction

**Figure 2. SKA-VLBI workshop participants**

The SKA-VLBI Key Science Projects and Operations workshop gathered together 68 scientists from 18 different countries (https://indico.skatelescope.org/event/539/; Fig. 2). We were happy to welcome both experienced scientists who have been developing Very Long Baseline Interferometry (VLBI) and the SKA for many decades, and a number of young researchers representing the flourishing and promising VLBI science, even from countries that have no VLBI facilities yet.

The aim of this workshop was to bring together these VLBI experts to work on new science cases under the umbrella of the high precision astrometry provided by SKA-VLBI. The discussions were intended to allow the optimal preparation for the full scientific exploration of the science that will be enabled by SKA-VLBI, resulting in custom-designed use cases and science projects in the many VLBI-related science areas identified in the SKA Science Book (Braun et al. 2015, RD003), as well as planning for surveys with traditional VLBI and SKA precursors and pathfinder facilities in preparation for possible SKA-VLBI Key Science Programmes.

The first day of the workshop was devoted to the introduction of different aspects of the SKA1 Observatory, focusing on the VLBI capability and the Portfolio of SKA-VLBI science cases compiled by the JUMPING JIVE project with the support of the SKA VLBI science working group (Garcia-Miro et al. 2019, RD004).

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The following three days, the main part of the workshop was organised into scientific sessions and discussions on how to realize SKA-VLBI Key Science Projects.

The scientific sessions focused on topics selected from the SKA High Priority Science Objectives. All these topics would benefit from the SKA-VLBI capability: active galactic nuclei (AGN), transient events, pulsars and fast radio bursts, stellar science and astrometry, complementing with prospects for the SKA-VLBI capability and development of VLBI in Africa. The scientific talks presented superb examples of all the science achievable at high angular resolutions and sensitivities provided by SKA-VLBI.

The discussions on the SKA-VLBI Key Science Projects were held within three working groups: AGN, stars and astrometry, and transients and pulsars. The groups addressed a list of questions proposed by the JUMPING JIVE WP10. The outcomes from the KSP discussions are presented in this document.

The wrap-up of the workshop was presented by *Professor Richard T. Schilizzi*, former SKA Director, who provided very good suggestions for harmonizing the VLBI world with the SKA. The workshop was a great success, and a number of the participants signed up as new members of the SKA VLBI science working group. The SKA Contact magazine Issue 2 echoed the success of this workshop (Annex 5).

The SKA-VLBI workshop was supported by the European Union’s Horizon 2020 research and innovation programme JUMPING JIVE [grant agreement No 730884] and the SKA VLBI Science Working Group. We especially thank the SKA Organisation for making this event possible. Complementary support is acknowledged from RadioNet [grant agreement No 730562].

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# 3 SKA Project Introduction

The first day of the workshop was dedicated to the introduction of the SKA Phase 1 project, its current status (prior to the COVID-19 crisis[1]), the different aspects of the VLBI capability for SKA1 and the outcomes from the review of the SKA-VLBI science cases (Fig. 3.1). The impact of the outcomes of JUMPING JIVE WP10 was presented throughout the first day.

In preparation for the discussion on the Key Science Projects the following day, the discussion points were established, and the different working groups were formed.


**Figure 3.1. SKA-VLBI workshop programme: first day**

## 3.1 SKA and VLBI

The SKA-VLBI workshop was opened by *Professor Phillip Diamond*, Director General of the SKA Observatory. The SKA is an international effort to build the World's largest radio telescope with the prime motivation of studying the history of the Universe in Hydrogen, but that will also enable transformational science in many other areas thanks to its high spatial, spectral and temporal resolution, polarimetric imaging with improved sensitivity and survey speed, and broad frequency coverage (Fig. 3.2). The importance of VLBI was outlined for

[1] Since the celebration of the workshop in October 2019 the SKA1 Project has achieved several major successful milestones: the approval of the System level Critical Design Review (December 2019), the approval of the Construction Proposal and Observatory Establishment and Delivery Plan (September 2020), and the establishment of the SKA Observatory, a new intergovernmental organisation dedicated to radio astronomy, (February 2021).

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supermassive black hole studies, radio supernovae, and the evolution of old stars, among others.


**Figure 3.2. SKA Key Science Drivers**

The SKA Organisation is a collaboration of 13 countries, with 4 countries that have joined in recent years and 3 or more in conversations to join in the future. The treaty to establish the SKA Observatory as an intergovernmental organisation was signed in Rome on the 12th of March 2019 with six countries confirming they will be SKA Observatory founding members. The total cost of the project is under about €2B (2020 euros) with a timeline that expects the SKA1 construction to be completed by 2027/28.

SKA precursors, such as MeerKAT and ASKAP, are already producing outstanding scientific results (Heywood et al. 2019, RD005; Bannister et al. 2019, RD006). Meanwhile, prototyping work for SKA1-Mid and SKA1-Low is progressing, with the construction of the first SKA antenna at the Karoo Astronomy Reserve and testing of different band receivers and the Aperture Array Verification System AAVS2 prototype Low station at the Murchison Radio Observatory. The SKA data flow challenge aspects are also progressing with the first precursor of a SKA Regional Centre, in Shanghai.

Professor Diamond assured the workshop that the SKA will have VLBI capability and stressed the importance that the H2020 JUMPING JIVE WP10 had to provide the resources to help define requirements, interfaces, use cases and an operational model. Garcia-Miro et al. 2018 (RD007) provided an excellent summary of how SKA1 will deliver its VLBI capability. This workshop will seek the scientific community views on the high-priority science areas for SKA as a VLBI element, requirements for SKA Regional Centres (SRC) and governance for global VLBI when SKA is operational.
The SKA science director, *Dr Robert Braun*, stressed the importance of the contribution of the SKA Science Working Groups (SWG) to the project, with more than 800 researchers from

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around the world, with active participation from the VLBI science working group. The major key science areas for SKA contribution were reviewed with the latest results on each field outlined (Fig. 3.3).


**Figure 3.3. The SKA Science Working groups and their science presented in 13 posters.**

For Cradle of Life science, the SKA will help in the understanding of planet formation, measuring grain growth through the planetesimal phase and resolving proto-planetary disks at sub astronomical unit scales (Hasegawa & Pudritz 2012, RD008).

The SKA will contribute to further testing of General Relativity. It will be able to detect all pulsars in our galaxy and even the first extragalactic pulsars further away than the Magellanic clouds, to probe General Relativity to its breaking point, and to try a direct detection of gravitational waves passing through the galaxy. The SKA would be sensitive to primordial gravitational waves and waves produced in supermassive black hole mergers.

The study of galactic evolution through neutral hydrogen detection with the SKA will help to understand galaxy assembly and the baryon cycle, and to determine the impact of galaxy environments in this evolution (Schaye et al. 2010, RD009; Oosterloo 2010, RD010).

The transient radio sky will be explored by the SKA with an estimated detection rate of 3k events per day. Fast radio bursts (FRBs), still of unknown origin, have further prospects for fundamental contributions to cosmology (Zhou et al. 2014, RD011).

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ESA's Plank mission provided a snapshot of the Universe when it was just 400,000 years old. Through the study of neutral hydrogen evolution along the Dark Ages, Cosmic Dawn and Epoch of Reionisation, the formation of the different structures can be traced back to when the universe was less than a billion years old. The SKA1-Low deep integrations will detect EoR structures and will probe the Cosmic Dawn in 3D for first post-Big Bang heat sources (Mutch et al. 2016, RD012; Barkana 2018, RD013).

Dr Braun also presented the SKA1 project science timeline (Fig. 3.4, Braun et al. 2017, RD014). Commissioning activities will start as soon as the first array assembly is completed (AA0.5) two years after the start of construction. As the arrays grow in the proceeding years there will be opportunities for the scientific community to be involved in different aspects of commissioning and science verification. Shared risk PI observations will start as soon as 3 months after the end of construction, accepting regular PI proposals 12 months later for the commissioned observing modes. Key Science Projects planning and proposals preparation will commence about 3 years before the end of construction, with KSP observing for the commissioned observing modes starting 12 months after the PI-led programmes.

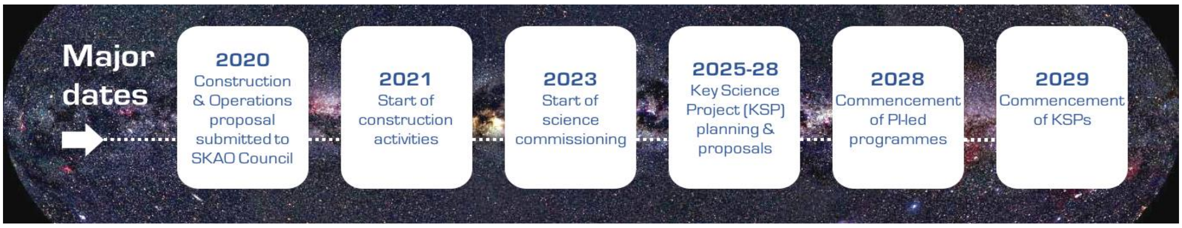


**Figure 3.4. The SKA1 project science timeline (Braun et al. 2017, RD014)**

The SKA project has started a series of Science Data Challenges to get the community familiar with the SKA data products and to start preparing the tools for science extraction and analysis for SWG and SRC applications. Due to the extremely large data volumes, the SKA project will provide already processed images, instead of the usual radio interferometric visibilities. The first Science Data Challenge (SDC1) was a SKA1-Mid science ready image data product in continuum (refer to Section 4.5). Future data challenges will focus on transients, HI emission and absorption, polarimetry and foreground removal.

The third talk in the morning was given by *Dr Francisco Colomer*, JIVE director and JUMPING JIVE project coordinator. He introduced the European VLBI Network and the Joint Institute for VLBI ERIC that gives support to the EVN and the users. The project "Joining up Users for Maximizing the Profile, the Innovation and the Necessary Globalization of JIVE" is an H2020 funded project with a duration of 50 months and approximately a 3 MEuro budget, and 12 partners including the SKA Organisation. The objectives of the project, divided into 10 work packages, are to advance the sustainability of JIVE, the development of new capabilities and the preparation for the future of VLBI. Work package 10 "VLBI with the SKA" provides support for the SKA integration and operations within the VLBI arrays, establishing details for

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interfaces between the arrays with the SKA (RD007), preparing a portfolio of SKA-VLBI science cases (RD004), presenting an operational model for SKA as part of the global VLBI networks (Garcia-Miro et al. 2020, RD015) and a report on SKA Key Science Projects with VLBI (this document). This work is led by JIVE and SKAO with the support of the SKA VLBI science working group and will be the seed of the establishment of a SKA-VLBI Consortium that will support the capability.

Dr Colomer concluded his talk by outlining that the real-time e-EVN network is a pathfinder for the SKA. The SKA1 science will greatly benefit from the long VLBI baselines providing an early insight into SKA2 science, and the SKA-VLBI know-how learned thanks to the JUMPING JIVE project can now be applied to the SKA precursors, such as MeerKAT that recently demonstrated fringes to the EVN.

The final talk before the lunch break by *Dr Zsolt Paragi* (and meeting co-chair Dr Antonio Chrysostomou) presented the workshop programme and goals and established the discussion points for the KSP parallel groups that are elaborated in Section 5. The VLBI contribution for SKA science was already outlined in the first SKA Science book (Taylor & Braun, 1999, RD016). The JUMPING JIVE project has studied the whole potential that the SKA1 telescopes provide, with access to southern skies, sub-μJy sensitivity on milliarcsecond scales, superior calibration and multi-beam capability for high-precision astrometry and high density of targets. The possibility of obtaining simultaneously other SKA1 products, and on a wide range of angular scales, will allow unique commensal applications.

Although SKA1 is still far in the future, its precursor MeerKAT is already providing great science, with the detection of bubbles in the galactic centre (Heywood et al. 2019, RD005) a key highlight. The SKA High Priority Science Objectives (HPSO, RD001) will greatly benefit from VLBI angular resolutions. For SKA1-Mid an impact can be made on pulsar astrometry (HPSO#5), proper motion and parallax distance measurement of stars and clusters (HPSO#26), the study of AGN feedback through HI absorption (HPSO#16), contribution to SKA continuum surveys for AGN versus star formation separation beyond $z > 0.1$ or gravitational lensing studies with cosmological applications, and on transient localisation and imaging (HPSOs#18-19), among others. For SKA1-Low the HI absorption can be studied for systems at high redshift (complementary to HPSO#13), pulsar scintillometry to study the ISM (related to HPSO#4), AGN jet termination hot-spots and transient localisation (HPSO#18).

The enthusiastic VLBI science working group has revealed itself as a fundamental piece to support the activity of the JUMPING JIVE project and consequently support the SKA project in the implementation of the SKA-VLBI capability and to exploit all the science it will facilitate.

Dr Paragi announced the formation of the parallel KSP discussion groups for the afternoon and presented the chairs that guided the discussions. Outcomes from the discussions were to be presented at the closing session of the workshop.

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## 3.2 Implementing SKA-VLBI

Session II was devoted to different aspects of implementing the SKA-VLBI capability. *Dr Evan Keane*, SKAO project scientist, presented the SKA observing capabilities and architecture (Dewdney et al. 2019, RD017). Phase 1 of the SKA will represent 3.3% of the collecting area planned for the complete Mid telescope while 40% of the Low telescope. From the planned receiver bands for the Mid telescope (at least 5), bands 2, 5 and 1 are included in the baseline design due to their higher scientific priority.

Both telescopes will have pulsar and transient search, pulsar timing, full Stokes continuum and spectral line imaging and VLBI capabilities, apart from the dynamic spectrum and high energy particle detection. The dramatic increase of gain versus survey speed for transient search for the SKA telescopes compared with operational instruments is represented in Fig. 3.5.

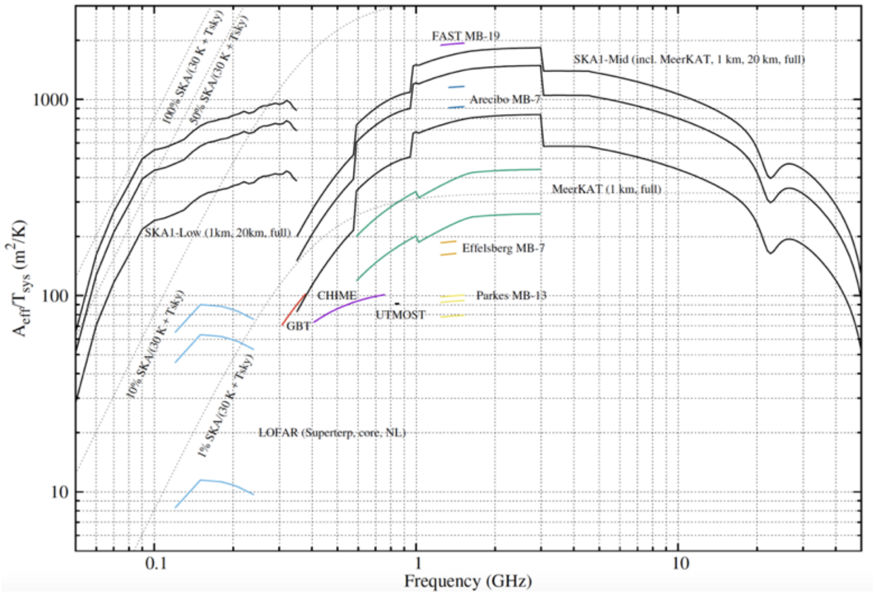


**Figure 3.5. SKA1-Mid and SKA1-Low gain versus survey speed compared with operational telescopes (Keane 2018, RD111).**

A key design feature of the SKA1 telescopes would be its flexibility, with the possibility to form up to 16 independent subarrays and perform many observing modes simultaneously on each subarray, with some correlator constraints in terms of observing bandwidth.

The science case for SKA Phase 1 has 13 High Priority Science Objectives (RD001), that could be realised during the first 5 years of full operations, dedicating 50-75% of the time, in the form of Key Science Projects. The remaining observing time will be used for PI-led projects from member countries while up to 5% (TBD) will be open time. Although the VLBI capability is not explicitly mentioned in these High Priority Science Objectives, it would be vital to the

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top science cases, such as astrometry related to pulsar timing studies and FRBs localisation. The VLBI community is doing a great job ensuring the VLBI capability for the SKA telescopes, specifically within the context of the JUMPING JIVE project and SWG efforts to demonstrate VLBI fringes with the precursors such as the MWA (Kirsten et al., this conference, Section 4.3).

Within the SKA project budget tension, we need to continue to advocate for the essential features in the design and those missing, such as more beams for VLBI. The SKA Science timeline should acknowledge the examples of recent successful new instruments and radio observatories, such as the SKA precursors and pathfinders, that are providing great science before full operation mode. And VLBI could be an example of this.

*Dr Cormac Reynolds*, co-chair of the VLBI science working group, gave an overview of the activities of the group. The group started as a focus group formed by the SKAO in 2014 to assist with the VLBI design for the SKA. In 2015 the group was reconstituted along the lines of the existing SWGs. Since then there has been a liaison with SKAO for all SKA-VLBI matters, including the formulation of system-level VLBI requirements for both SKA1-Mid and Low telescopes and assisted in the preparation of related ECPs. Additionally, the group contributed to the SKA Science book (RD003) with several chapters focused on VLBI science and has supported the JUMPING JIVE project. After the SKA General Science meeting in 2019, the group became a science working group transitioning from a technical to a science focus group.

The VLBI group has an open membership, with currently 78 members, representing 19 countries, divided into 29 core members and 49 associate members. The group is co-chaired by Tao An and Cormac Reynolds. Information about the group can be found here: http://astronomers.skatelescope.org/science-working-groups/vlbi/.

Future activities are the contribution to the SKA VLBI operation’s model development (RD015). For this, it will be necessary to improve the coordination between the VLBI networks in terms of proposal submission, time allocation and correlator resource allocation. There is an urgency to push for early deployment of the VLBI capability, for early science opportunities with the SKA and provide an engineering testbed for commissioning activities. The group will make sure of embedding VLBI in all relevant KSPs increasing the cross-SWG interaction and possibly formulate a KSP for VLBI science.

The talk by the SKA-VLBI scientist, *Mrs. Cristina García-Miró*, reviewed the SKA-VLBI capability that has been presented in the JUMPING JIVE deliverable D10.1 “Details on VLBI Interfaces to SKA Consortia” (RD007). VLBI will bring high angular resolutions to the SKA high priority science objectives allowing SKA2 science sooner. It will also help to independently commission the SKA telescopes and could provide early public relations opportunities. And most importantly, it brings together an enthusiastic user community. The SKA telescopes will provide multiple VLBI beams with a boost in sensitivity to the µJy regime and access to the Galactic Centre and southern skies, with superior amplitude and polarisation calibration for the VLBI observations and simultaneous observing modes to support novel science cases.

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The SKA1-Mid and Low telescopes will participate in VLBI observations providing up to 4 standard format VLBI beams produced from a phased-up core subarray, with a size that will balance FoV and sensitivity requirements in the beams. The SKA1-Low will be able to perform simultaneously all observing modes within each subarray, but SKA1-Mid processing resources are limited and will allow for all the observing modes to be performed simultaneously but with a bandwidth limitation, providing just one observing mode with full bandwidth at Band 5 (Table 3.1). The caveat is that Band 5 SKA imaging projects that would require all Mid processing resources will not allow for commensal VLBI observations.

**Table 3.1. Examples of commensal observing modes within a subarray for SKA1-Mid for different observing bands, number of VLBI beams and bandwidths. The correlator is limited to 26 frequency slice processors (FSP).**

| Band | VLBI + coarse Vis | Imaging | PSS | PST | Zoom |
|---|---|---|---|---|---|
| **Band 1** (0.35-1.05GHz) | 4beams full (700MHz) (8 FSP) | Full (4 FSP) | 1500b 300MHz (8 FSP) | 16b full (4 FSP) | 2 (2 FSP) |
| | 4b 600MHz (6 FSP) | Full (4 FSP) | 1500b 300MHz (8 FSP) | 16b full (4 FSP) | 4 (4 FSP) |
| **Band 2** (0.95-1.76GHz) | 4beams full (810MHz) (10 FSP) | Full (5 FSP) | 1500b 300MHz (8 FSP) | 16b 600 MHz (3 FSP) | 🚫 |
| | 4b 600MHz (6 FSP) | Full (5 FSP) | 1500b 300MHz (8 FSP) | 16b full (5 FSP) | 2 (2 FSP) |
| **Band 5a/b** (4.6-8.5GHz & 8.3-15.3GHz) | 2/4beams 5/2.5GHz (26 FSP) | 🚫 | 🚫 | 🚫 | 🚫 |
| | 4beams 600MHz (6 FSP) | 512MHz (3 FSP) | 1500b 300MHz (8 FSP) | 16b 512 MHz (3 FSP) | 6 (6 FSP) |
| | 14beams 500MHz (21 FSP) | 500MHz (3 FSP) | 🚫 | 🚫 | 3.1MHz (1 FSP) |
| | 🚫 | Full (26 FSP) | 🚫 | 🚫 | 🚫 |

Although the SKA baseline design will only provide 4 VLBI beams per telescope[2], the correlator's design could allow for more, either trading bandwidth as for the Mid case without additional costs or adding extra processing resources as for the Low case, with budget implications.

*Dr Antonio Chrysostomou*, head of SKA Science Operations group, reviewed the SKA Operational model (RD018). The functional structure of the SKA (Fig. 3.6) is composed of one observatory that operates two telescopes, SKA1-Mid and Low, located in three different sites, the telescope locations in South Africa and Australia and the Global Headquarters in the UK,

[2] This document presents the successful outcomes from an Engineering Change Proposal that was presented after the workshop to the SKA Project that will provide more than 4 beams from the SKA1-Mid telescope (Section 6.2).

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plus facilities at each host country to enable the operation of SKA: Engineering Operations Centre (EOC), Science Operations Centre (SOC) and Science Processing Centre (SPC).

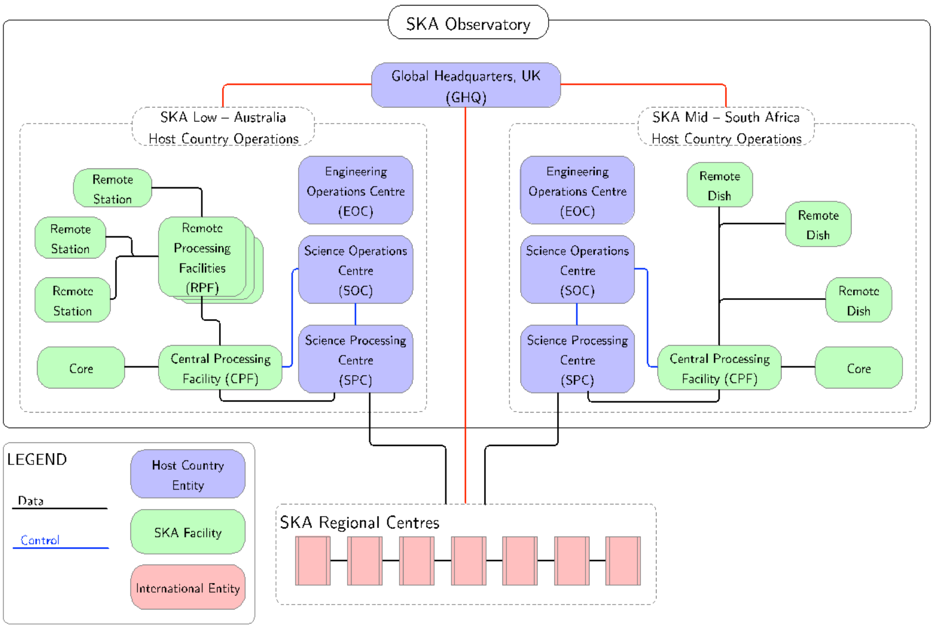


**Figure 3.6. SKA Observatory functional structure**

The SKA operational model contemplates conventional features such as periodic proposal cycles, service observing and 24/7 operations. It will accept standard PI proposals, Key Science Projects, long term proposals and coordinated proposals. More challenging features are the use of dynamic scheduling, the handling of operations from a different continent, high operational availability, rapid response to transients and ToOs and the possibility to perform different scientific programs commensally. It will provide different observing modes: imaging (in continuum and spectral line), beamforming for pulsar search, pulsar timing and VLBI and transient search.

The capability to divide the array into subarrays, using pre-defined templates, allows the execution of more than one observation at the same time. Three types of commensality are contemplated: in the data where different projects use the same data products for different science goals, in the observation where different projects use different data products produced from the same collected signal, and multiplex where the telescope is divided into independent subarrays performing different observations at the same time.

The operational model is necessarily very distributed, it would be important to identify commonalities in the operation of SKA1-Low and Mid. The operational workflow is divided into three phases: phase 1 for proposal management, phase 2 for observation execution and phase 3 for data processing.

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Managing the data flow is one of the greatest challenges for SKA. The large data rates require robust signal transport and compute power, limited by the rate at which the data can be processed at the Science Data Processor (SDP) and delivered to the SKA Regional Centres (SRCs). For planning the observing programme of the SKA, the SDP will become a schedulable resource of the telescope.

Each observing mode has specific data products. These observatory data products (ODPs) are generated at the observatory at the observation level (calibrated data products generated by SDP) or at the project level as specified in the proposal (e.g. combination of observation-level data products). Advanced Data Products (ADPs) are generated by users at the SRCs, through the detailed analysis and modelling of ODPs.

The SRCs will follow a global collaborative model, as the products from SDP will need advanced tools for analysis and modelling before publication, data volumes would be so large that it would be unfeasible to deliver raw data directly to end-users, and the community of scientists is geographically distributed. This global network will provide a platform for collaborative science, transparent and location-agnostic interface to users, access to project data, a place for s/w analysis, and tools development. The SRCs will maintain the data flow of the observatory to the SKA community, provide resources for data processing, provide data storage and tools to realise the SKA Science Archive and provide support to users for SRCs activities.

Further discussion about the SRCs and their support to VLBI operations was given by *Dr Tao An*. The global network of SRCs will be geographically distributed in order to support regional users with diverse science focuses. For VLBI it would be necessary to define how the SRCs could better support the SKA-VLBI operations in the different phases (preparation, commissioning and operation), how the SKA data products will be linked to the VLBI products from the correlators centres, and what advanced data products may be required and the policies for data access. A proto-SRC using few VLBI KSP use cases could help to understand the challenges in areas such as data transfer, correlation including multiple beams instruments and data analysis software, and possibilities for distributed correlation. An example is the East Asian SRC with the aim to support the Asian SKA users and KSPs. A forum is being formed with a user community of 300+ members with interests in SKA science and East Asian VLBI Network (EAVN) science (and therefore in SKA-VLBI science). The China SRC prototype in Shanghai is the result of an alliance of observatories, universities, ICT companies and supercomputing centres. It is able to support 200 Tflops and 2PB buffer and is already processing the MWA and the ASKAP pipelines. There are plans for an end-to-end connection between Cape Town – Dwingeloo – Perth – Shanghai to test the future SRC network.

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## 3.3 SKA-VLBI Science Use Cases

Session III of the workshop was devoted to SKA-VLBI science cases. *Dr Richard Dodson* opened the session by presenting the ultra-precise astrometry science case that will be crucial to many of the SKA-VLBI projects. Radio astrometry with existing instruments is a challenging technique that requires improvement of the calibration methods, currently limited by systematic errors. Under these circumstances, increasing the sensitivity does not improve the accuracy. For the next-generation instruments, it would be important that their enhanced sensitivity can be fully exploited, and the new astrometry requirements are not designed out.

Phase-referenced astrometry is limited by systematic errors that are dominated by the atmospheric propagation effects, caused by the ionosphere and the troposphere in the static and dynamic regimes. These astrometric errors strongly depend on the angular separation between the target and the reference source, the switching time and the observing frequency.

The established strategies are to use conventional phase referencing with calibrators within degrees from the target or in-beam phase referencing with up to a few arcmin separation, combined with advanced atmospheric calibration methods to reduce the static effects (Fig. 3.7).

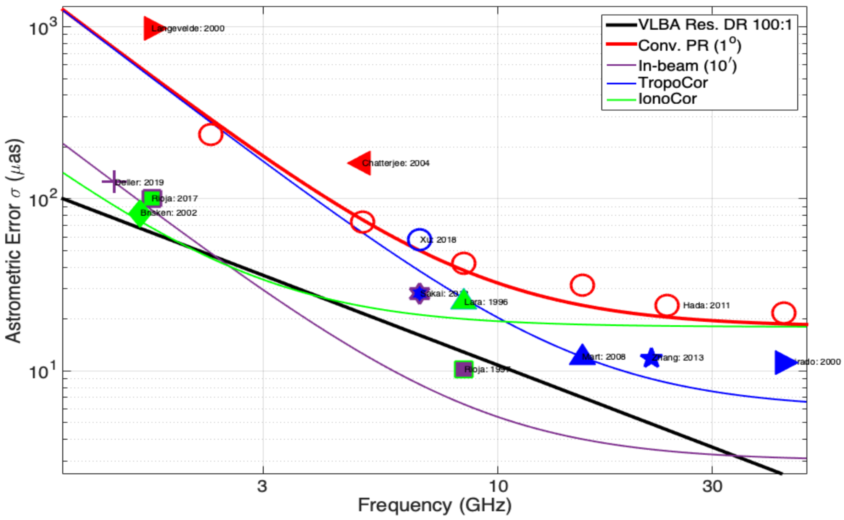


**Figure 3.7. Astrometry static errors as a function of frequency for VLBA observations using different techniques compared with the theoretical errors (black line).**

For Mid-frequencies that are dominated by tropospheric errors, the strategy is to calculate the residual path length at zenith with dedicated all-sky observing blocks (i.e. geodetic-blocks) included in the observing schedule. For frequencies below 8 GHz, this solution does not work, and one needs to solve for the dispersive delay for the line of sight, and therefore account for

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the ionospheric direction-dependent effects. There are different strategies to correct for ionospheric effects: observe two different bands, usage of narrow channels within the observed band (Brisken et al. 2000, RD019) or include dedicated low-frequency ionospheric excision blocks (i.e. ICE-blocks, Dodson et al. 2017, RD020) in the schedule. Nevertheless, in-beam phase-referencing achieves similar results as conventional phase-referencing with ionospheric correction, but calibrators are sparse above L-band and require correlators able to solve for different phase centres.

The new strategies are source frequency phase referencing (SFPR) and multi-frequency phase referencing (MFPS) for higher frequencies and multi-view phase referencing for frequencies below 10 GHz. The widely applicable observing strategy for multi-view is to switch very fast between several reference sources and the target. But if multi-beam capability is available, the systematic errors are reduced, and the observation reaches the thermal noise limited regime. The MultiView technique (Rioja et al. 2017, RD021) uses multiple reference sources that could be placed further away (few degrees) and performs a 2D interpolation in the visibility domain for the target’s line of sight. With a minimum of 4 beams, MultiView solves for the 2D planar structure, but the troposphere and the ionosphere have non-linear components.

At very high frequencies the troposphere behaves linearly for short baselines but not for the longer ones. Garrett Kettering (in prep, RD022), shows the behaviour of the troposphere at 230GHz for Submillimetre Array (SMA) observations. Non-linear residuals are <0.1mm but weather dependent, and therefore worse than average day.

For lower frequencies, Murchison Widefield Array (MWA) observations at 150MHz (Fig. 3.8, Rioja et al. 2018 RD023) have shown that direction-dependent corrections are required to correct for phase slopes across the array of +-60 degrees (Dodson & Rioja 2018, RD024). The Low-frequency Excision of Atmosphere in Parallel algorithm (LEAP) provides a station-based direction-dependent visibility correction, more suitable than former array-wide linear shift per snapshot image corrections (Cotton et al. 1999, RD025). The LEAP algorithm will be applicable to the SKA1, allowing astrometry at 1.5 GHz with better than 10 μas accuracy for >1000:1 dynamic range.

In summary, the MultiView technique should deliver 1 μas astrometry for frequencies above 6 GHz, an order of magnitude improvement with respect to current capability (Rioja & Dodson 2020, RD026). Among the main science goals for 1 μas astrometry are the precise determination of distances to binary pulsars in our Galaxy (~1%) for strong general relativity tests, the measurement of distances to masers in the LMC for system dynamics studies and the precise determination of stellar orbital parameters for the detection of planetary bodies.
The next-generation VLBI facilities will provide an order of magnitude increase in sensitivity that could be fully exploited using new astrometric capabilities, such as the multi-beam SKA capability, that should provide more than 4 simultaneous beams (at least up to 8) within the field of view of the co-observing single dishes.

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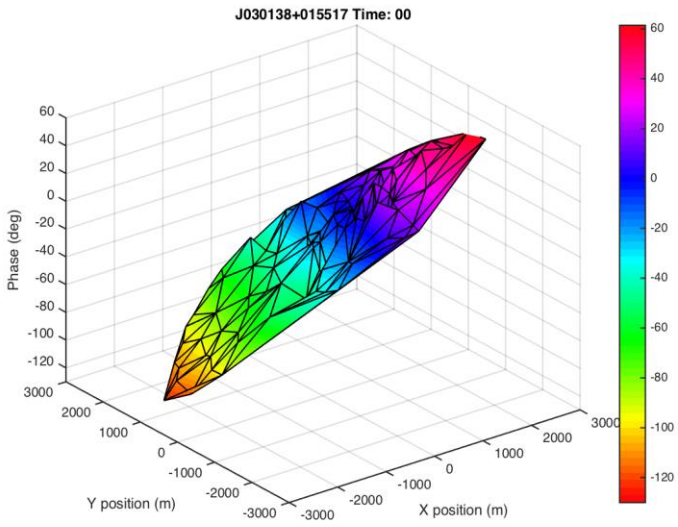


**Figure 3.8. MWA-2 ionosphere phase surface across the array for a worst-case 30-sec snapshot. Rioja et al. 2018 (RD023)**

The second talk of the third session by *Cristina García-Miró* reviewed the outcomes from the SKA-VLBI science cases study (JUMPING JIVE deliverable D10.3, RD004) that was prepared with the support of the VLBI science working group. The portfolio presented a total of 30 science cases, six cases already published in the SKA1 scientific use cases document (RD027) that were updated with the latest capabilities, 16 new cases for SKA1-Mid, 7 new cases for SKA1-Low that previously had none, and one for both SKA1 telescopes. The use cases cover a wide range of science topics with quests that are only achievable thanks to the SKA-VLBI capability, from continuum surveys, galaxies and active galactic nuclei, to stars, pulsars and transients, high precision relative and global astrometry with different applicability and cradle of life and planets.

Although the number of use cases presented is quite different for both telescopes, the total time requested is similar showing that VLBI could exploit both SKA telescopes similarly. The SKA1-Mid projects are equally divided between low and high frequencies, with at least 8 projects requiring dual-band observations covering both ranges. Most of the high-frequency projects require broad bandwidth and therefore are affected by the Band 5 design split, but the possible Band 6 extension (Section 4.5) could benefit at least four projects.

From the observing strategy point of view, all use cases can also be equally divided between single epoch observations for surveys or several epochs for variability follow-up and parallax measurement. At least 5 projects are time-critical, triggered internally or externally to the SKA1 and could also produce triggers.

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The VLBI beams are always produced from a core subarray with a size chosen as a trade-off between FoV and sensitivity in the beams, and beamforming stability. For 6 use cases at least two core subarrays are needed to support dual-band observations. For most of the cases, the number of VLBI beams needed exceeds the SKA requirements that provides only 4 beams in total. More beams are needed either for high precision astrometry or to cover high density of targets within the FoV as shown in Figure 3.9. An engineering change proposal[3] was passed that allows for an increase in the number of beams available from SKA1-Mid. The VLBI aggregated data rates are manageable and can be recorded with current technology and electronically transferred to the external VLBI correlator.

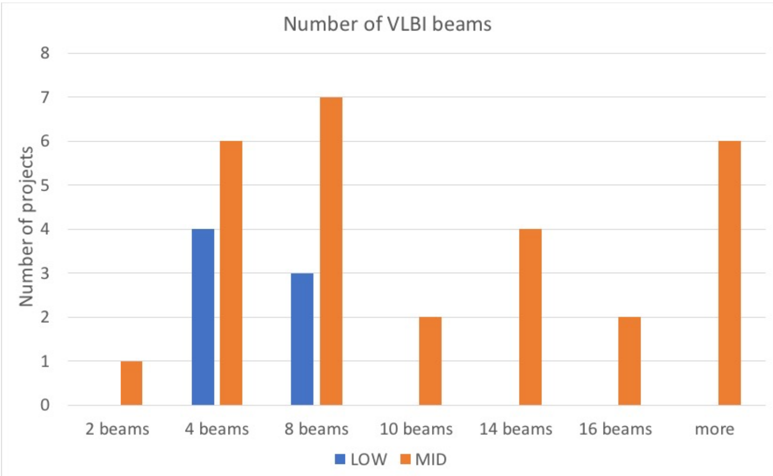


**Figure 3.9. Number of VLBI beams needed to support the SKA-VLBI science cases with the SKA1 telescopes (RD004).**

Together with the VLBI beams, all science cases need simultaneous SKA imaging produced mostly from the whole array for calibration purposes. Other SKA science data products requested simultaneously are polarimetric products, spectral line imaging and for few cases, pulsar and transient buffer data. The showstopper is that for SKA1-Mid the processing resources are insufficient to support full Band 5 Imaging and VLBI in a simultaneous way. With careful management of the processing resources, at least 10 cases could be observed commensally with other SKA1 projects, such as the continuum and spectral line surveys, the pulsar scintillometry and the global astrometry cases.

From the operational model point of view, all use cases would need established policies for SKA-VLBI observations support, including policies for ToO, triggers and overrides. For SKA1-Low and Band 1 observations the VLBI networks would need to be further developed.

To finalise the session *Dr Zsolt Paragi* introduced the Key Science Projects discussion (Section 5). Different discussion groups were formed, covering four main science topics: AGN, pulsars, transients and stars/astrometry.

[3] Refer to Section 6.2 for an Engineering Change Proposal submission and outcome.

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# 4 SKA-VLBI Science

The following three days of the workshop were mainly devoted to the wealth of science that SKA-VLBI will realize (Figs. 4.1, 4.2 and 4.3). These high-impact science cases dovetail with most of the SKA high priority science objectives (HPSO). The SKA-VLBI extreme resolving power will build the foundation and will help accomplish the science of the full SKA2 before it is even completed.

The different scientific talks were structured in sessions dedicated to the following main topics: Active Galactic Nuclei (AGN), transients, pulsars and Fast Radio Bursts (FRBs), stellar science and astrometry, prospects for the SKA-VLBI capability and the development of radio astronomy in Africa. The talk ***SKA and VLBI historical perspective on current challenges*** by *Professor Richard T. Schilizzi* is summarised in Section 7.


Figure 4.1. SKA-VLBI workshop programme: second day


Figure 4.2. SKA-VLBI workshop programme: third day

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**Figure 4.3. SKA-VLBI workshop programme: fourth day**

## 4.1 Active Galactic Nuclei

Historically Active Galactic Nuclei (AGNs) have been one of the main targets of VLBI science. This session explored how VLBI has recently changed the paradigm with the ability to perform wide-field surveys. Together with SKA-VLBI it will build a complete sample of resolved high-z AGN and will contribute to the understanding of the co-evolution of the central supermassive black holes and their hosts.

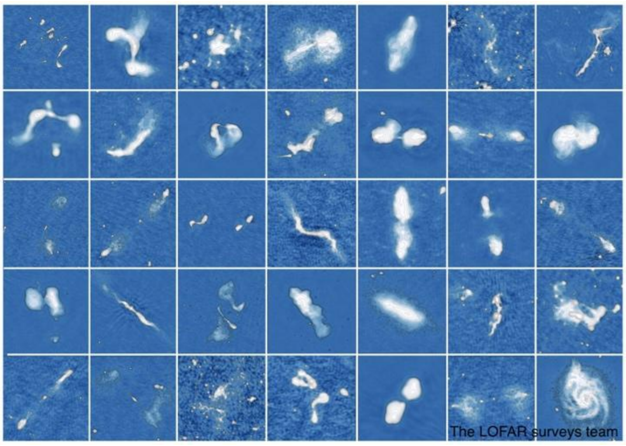


**Figure 4.4. LOFAR Two-meter Sky Survey – LoTSS (Shimwell et al. 2019 RD028, Williams et al. 2019 RD029, Duncan et al. 2019, RD030)**

Studies of Active Galactic Nuclei (AGNs) at lower frequencies (of the order of MHz) brings a wealth of information. It allows reaching fainter populations, capturing the low-frequency absorption and the low energy cut-off (due to synchrotron self-absorption and free-free

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absorption) and probing the lower pick frequencies for high-z. *Dr Leah Morabito* gave a review on the results of ***AGN surveys at low frequencies with the International LOFAR Telescope and a look towards the MHz future.***

The LOFAR two-meter sky survey (LoTSS, Fig. 4.4) with more than 320k sources detected and about 70% of the total identified, is contributing to the understanding of the different AGN populations, such as the interpretation of Fanaroff-Riley Class-I (FR-I) radio galaxies as a low-power population of Class-II objects (FR-II) (Mingo et al. 2019, RD031).

Moreover, the combination of high angular resolution imaging and sensitivity at the lower frequencies provided by the International LOFAR Telescope (ILT) is revealing as a unique probe for AGN science. Examples of science cases are the disentanglement between AGN and star formation activity (Fig. 4.5, Hardcastle et al. 2019, RD032) and the characterisation of the smallest Fanaroff-Riley radio galaxies. For radio loud AGNs, it allows the characterisation of high redshift sources and the study of the hot spot physics and the spectral modelling. For radio quiet AGNs, it reveals the origin of the radio emission, helping in the core identification and the study of small-scale jets or winds. It also contributes to gravitationally lensed galaxy studies.

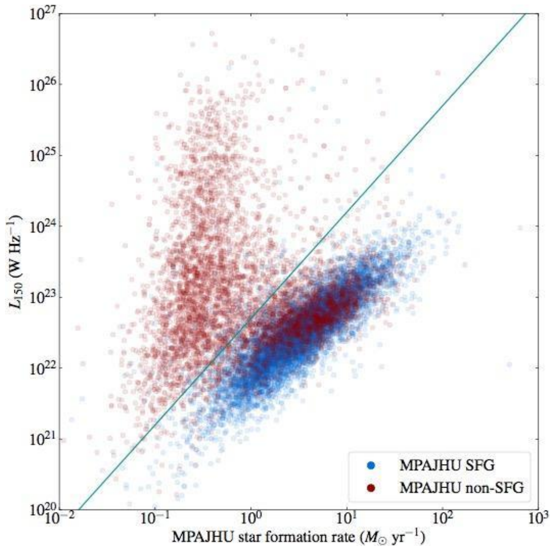


**Figure 4.5. Radio luminosity as a function of star formation rate for a sample of galaxies showing two distinct populations, galaxies with star formation and without (Hardcastle et al. 2019, RD032)**

Compared with the ILT, low frequency AGN studies with SKA-VLBI will provide better sensitivity with better frequency coverage, milliarcsecond resolution at the top of the band but a smaller field of view. The greatest advances in the field facilitated by SKA-VLBI will be the spectral modelling for the hot-spots in radio loud AGN; the capture of the origin of radio emission in radio quiet AGN; and the build of a sample of resolved high-z AGN. It was recommended to start with a well-known field to complement existing data (e.g. COSMOS,

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Herrera-Ruiz et al. 2017, RD033), exploit synergies with other surveys, such as the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) survey, and apply the lessons learned from ILT, both technical and scientific.

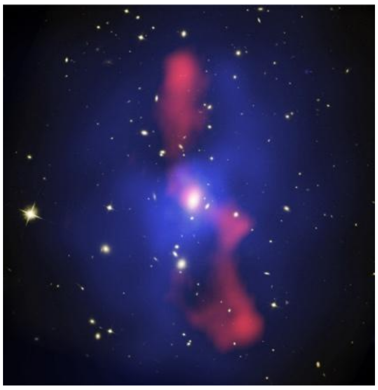

**Figure 4.6. Negative AGN feedback in MS0735.6+7421, with X-ray emission in blue, radio emission in red and optical emission in white (McNamara & Nulsen 2012, RD034)**

***Wide-Field VLBI is the SKA era*** talk by *Dr Jack Radcliffe* reviewed the motivation for radio deep-field surveys and the future role of SKA-VLBI. McConnell et al. 2012 (RD035) showed that the mass of supermassive black holes (SMBH) is correlated with the bulk properties of the nearby galaxies. This implies a co-evolution of the SMBH and its hosts, and therefore feedback between both that could be either positive, negative or both (Fig. 4.6).

To investigate this evolution, it is necessary to find and identify all the AGNs in the radio deep-field surveys. Different techniques are used, using emission at different wavelengths, typically the study of the X-ray emission, the mid-infrared emission or the radio excess, but there are many more strategies (e.g. optical-UV excess, SED fitting, Gamma-rays, variability, etc.). The X-ray emission is common to all AGN; however, the Compton-thick tori can obscure this emission, especially soft X-rays. The mid-infrared emission is correlated with the AGN luminosity and is good to detect obscured AGN but only the most luminous. The radio emission traces both star formation and AGN activity. For star-forming galaxies, there is a tight correlation between FIR emission and radio that is not hold for AGNs. But although the bolometric IR measurements are very reliable, they require both FIR and NIR data.

AGNs can also be identified via their morphology but most are unresolved at typical radio resolutions and µJy sensitivities. And here is where VLBI plays a role as an AGN finder. A typical VLBI array with a low filling-factor means that large scale structures interfere destructively, and therefore the array has low sensitivity to the extended emission but high sensitivity to point-like sources. Hence, VLBI only detects compact emission with high brightness temperature ($T_B > 10^5$ K) which can only be produced by AGNs at redshifts z > 0.1.

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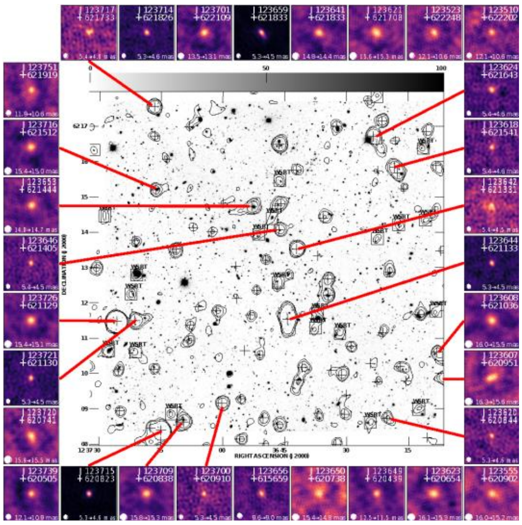

**Figure 4.7. GOODS-N field, a 0.5-degree survey with the EVN at 1.6 GHz using 699 phase centres (Radcliffe et al. 2018, RD037)**

The VLBI technique is the one that identifies the largest number of AGNs. There is no single technique that can reliably identify all VLBI-selected AGNs. Therefore, the approach is to use VLBI to survey large sky areas to find AGNs. Nowadays multiple degrees can be easily surveyed using VLBI (Deller & Middelberg 2014, RD036; Herrera-Ruiz et al. 2017, RD033; Radcliffe et al. 2018, RD037, Fig. 4.7). Wide-field VLBI techniques have recently improved, with the use of multiple correlation phase centres allowed by the new software correlators and innovative self-calibration techniques to reach thermal noise levels down to the µJy regime (e.g. multi-source self-calibration, Radcliffe et al. 2016, RD038). All these techniques will have a direct application to the SKA-VLBI multi-beam capability.

But wide-field VLBI can do so much science: identification of supermassive black hole binaries (Deane et al. 2014, RD039; Herrera-Ruiz et al. 2017, RD033; Radcliffe et al. in prep, RD040); studies of gravitational lenses (Spingola et al. 2019, RD041); radio supernovae and low luminosity AGNs (Radcliffe et al. 2019, RD042); and much more. The future surveys with SKA-VLBI will show us how the VLBI sky looks like at < µJy sensitivities.

Until the next-generation instruments SKA2 and ngVLA are ready, SKA1-VLBI fills a resolution parameter space that is not yet covered. Furthermore, a combination of imaging using multiple arrays with low- and high-resolution instruments could provide SKA2 science now.

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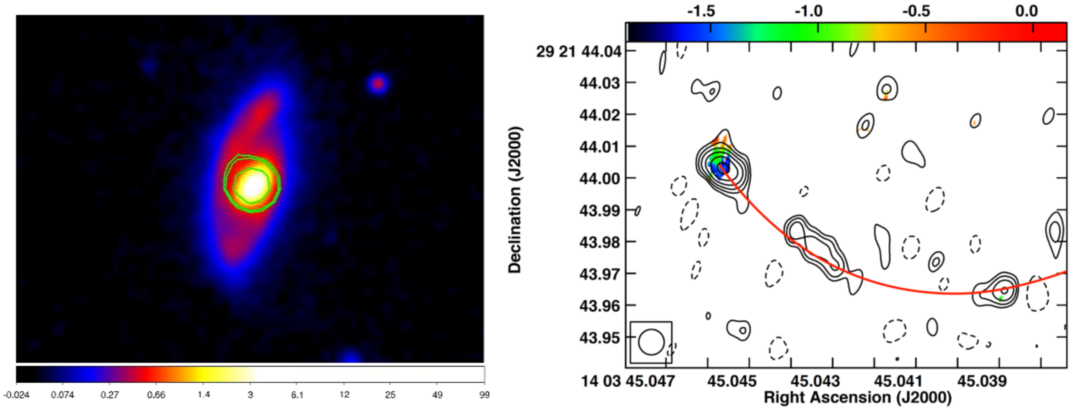


**Figure 4.8. Left: *g*-band SDSS image of KISSR 434 and FIRST 1.4 GHz radio contours; Right: The 1.5 GHz VLBA contour image of KISSR 434 with the 1.5–4.9 GHz spectral index image in color (Kharb et al. 2019, RD044)**

A special type of radio-quiet AGNs is those with double-peaked emission lines in their optical spectra. This feature could reveal binary black holes (BBH) candidates. *Dr Preeti Kharb* presented the study ***A look at double-peaked emission line AGN with VLBI*** of a sample of radio-quiet Seyfert 2 and LINER galaxies selected from the KPNO International Spectroscopic Survey (KISSR, Salzer et al. 2000, RD043).

The study used phase-referenced dual-frequency VLBI observations revealing that weak radio AGN have parsec-scale core-jet radio structures, typically one-sided most probably due to Doppler boosting. At least one case from the sample is a parsec-scale binary black hole (BBH) candidate (Kharb et al. 2019, RD044). A couple of cases presented curved jets, that may be a precessing signature produced by a BBH (Fig. 4.8). However, in most cases, signatures of strong jet-medium interaction are likely to be responsible for the splitting of the emission-line peaks (Kharb et al. in prep, RD045).

SKA-VLBI high angular resolution and sensitivity will definitely contribute to our understanding of jets in radio-quiet AGNs.

## 4.2 Transients

This session and the following (Sect. 4.3) presented excellent examples of the current hot topics on transient and time-domain astronomy: gravitational waves mergers and Tidal Disruption Events (TDE); core-collapse supernovae and Gamma Ray Bursts (GRB); accreting stellar mass black holes and ultra-luminous X-ray sources (ULX); to finish with pulsar science applications for Interstellar Medium (ISM) studies and the mysterious Fast Radio Bursts (FRB).

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The first talk by *Dr Pikky Atri* on ***Accreting Galactic black holes with SKA-VLBI*** stressed the importance of these objects as excellent probes to study the physics of relativistic jets, complementing the studies from the jets in AGNs. The galactic systems have several advantages: variability timescales of the order of weeks instead of years and the possibility of detection of the two-sided jets, allowing for the dynamics and physics of the system to be solved.

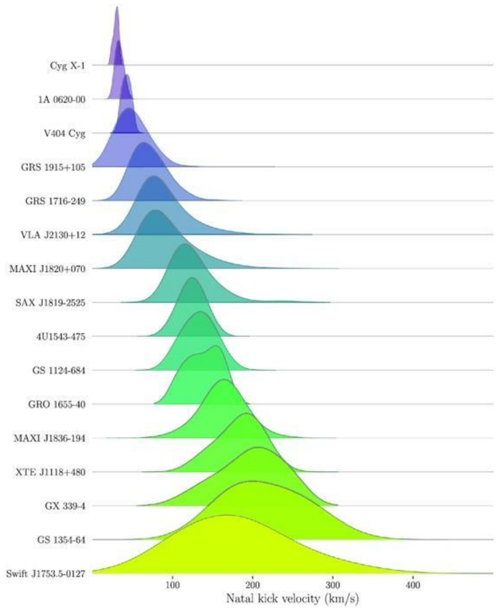


**Figure 4.9. Natal kick velocity distribution (Atri et al. 2019, RD048)**

SKA-VLBI will provide ultra-sensitive detections with better a-priori amplitude calibration to access fainter and quieter galactic black holes and look further into our galaxy. The SKA superior polarisation calibration and sensitivity will help to provide information on the magnetic field structure from the two-sided jets to decouple between different models for the ejecta (discrete plasmons or shocks in continuous jets). Moreover, SKA-VLBI multi-frequency observations will probe different jet locations and the environment of the binary systems (Paragi et al. 1999, RD046). Lastly, ultra-accurate astrometry demonstrated by simulations of the SKA-VLBI MultiView technique (Jimenez-Monferrer et al. 2010, RD047, Sect. 6.1.1) will allow detailed studies of core shifts and proper motion of the components, jet precession and orbital parameters, and the determination of more accurate parallaxes and system proper motions to understand the birth place and birth mechanisms of these stellar mass black holes and the distribution of natal kick velocities (Atri et al. 2019, RD048, Fig. 4.9).

Studies of accreting stellar mass black holes should have a prominent presence on the SKA-VLBI Key Science Projects, taking advantage of a sensitive and flexible VLBI network that would include the SKA telescopes, and would need to be available on short notice during the outbursts.

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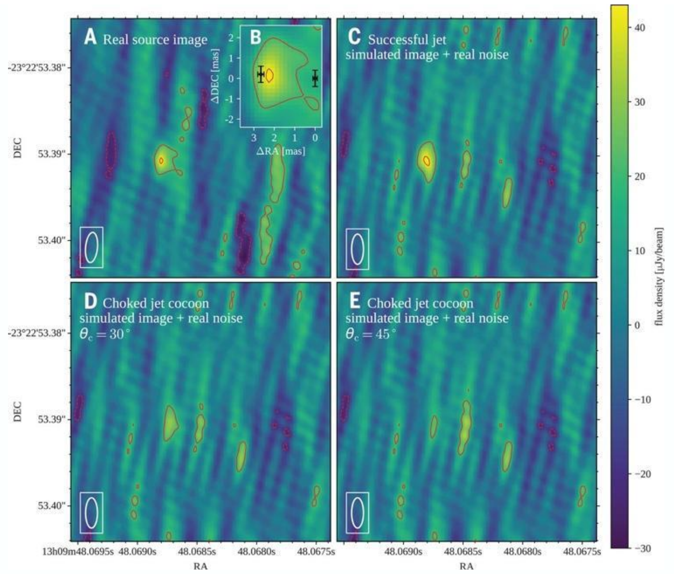


**Figure 4.10. Observed and simulated radio images of GW170817 (Ghirlanda et al. 2019, RD052)**

A review of the VLBI contribution to the study of the gravitational wave events was given by *Dr Marcelo Giroletti* with the title ***GW-EM counterparts VLBI follow-up***. Over the last years, we have witnessed the start of the era of "multi-messenger" astrophysics, primarily thanks to electromagnetic follow up of gravitational wave events detected by the LIGO-Virgo interferometers. The gravitational wave detections provide access to dark sources that give clues on fundamental physics, general relativity, cosmology, etc. They also allow the exploration of a broader range of parameters, accessing much larger energies (>> PeV) but with very poor angular resolutions. Complementary and coordinated high angular resolution follow up in multi-wavelengths has been revealed as completely necessary to understand their nature.

VLBI has played a primary role in the characterisation of the physics of the first and the only binary neutron star (BNS) merger detected until now in the electromagnetic spectrum, known as GW 170817. This binary neutron star merger resulted in the production of a short GRB (Abbott et al. 2017, RD049) detected by Fermi and localised within a 28deg$^2$ sky area. It also produced a kilonova (Pian et al. 2017, RD050) as suggested by the optical/IR signatures of radioactive-decay powered emission from the expelled material and subsequent afterglow emission in different wavelengths that lasts days/weeks and allows for localisation and hence identification.

The radio emission was detected at last (Hallinan et al. 2017, RD051), as the material moved away from the merger, producing a shockwave in the interstellar medium. Questions such as how the ejecta advances in the surrounding medium and whether a jet is formed or not require the high angular resolution provided by VLBI. Global VLBI observations by Ghirlanda et al. 2019 (RD052, Fig. 4.10) discerned between the possible models (Mooley et al. 2018a,

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RD053), showing that the BNS merger was able to produce a relativistic jet, with a narrow opening angle, slightly misaligned to our line of sight, and relativistic motion in agreement with Mooley et al. 2018b (RD054).

At least 10% of BNS mergers should behave in a similar manner, with the order of one event per year detectable with VLBI. These studies require high sensitivity and the high angular resolutions provided by a Global VLBI array, together with light curve information at different frequencies to constrain the models. Different campaigns were organised to follow up the mergers observed during O3, with the e-EVN, the e-MERLIN, MeerKAT plus VLA, ATCA, ASKAP, VLBA and the Italian radio telescopes.

Future challenges include the discovery, localisation and resolution of similar BNS jets, equivalent studies on the BH-NS events and the study of the polarised emission. The VLBI capabilities for the SKA will significantly improve the scientific return in this field. SKA will provide a sensitive element that would need good supporting VLBI arrays, with compatible observing bands and good RFI control.

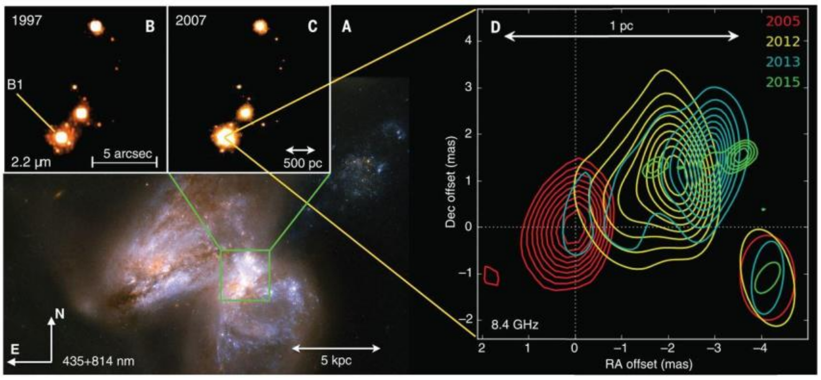


**Figure 4.11. The transient Arp 299-B AT1 and its host galaxy (Mattila et al. 2018, RD060)**

In the last decades, VLBI has been crucial for studies of core-collapse supernovae (CCSNe) to resolve their shell structure and study their expansion in detail (Marcaide et al. 1995, RD055; Marti-Vidal et al. 2011, RD056). VLBI has also contributed to the understanding of the gamma ray bursts (GRBs), also attributed to collapse events, revealing the production of jets and disentangling the effects caused by the environment (Mesler et al. 2012, RD057; Napo et al. 2017, RD058). *Dr Miguel Perez-Torres* explained in his talk titled ***Supernovae and Nuclear Transients with VLBI*** that current studies are aiming to image young core-collapse events in the nearby universe to build a reference sample. With the SKA sensitivity and the SKA-VLBI angular resolution, it will be possible to image relatively old supernovae (SNe) and supernova remnants (SNRs), those that exploded in the last 50 years, bridging the gap between the very early phases of the supernova explosions and the transition to the remnant phase.

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While unbiased all-sky surveys in different wavelengths are discovering thousands of CCSNe, the transients in the nuclei of galaxies are largely overlooked. However, VLBI has recently revealed supernova factories that are hidden behind the dust in the centre of galaxies (Perez-Torres et al. 2009, RD059). Moreover, VLBI has also detected tidal disruption events (TDE), the destruction of a star swallowed by a supermassive black hole, demonstrating the production of relativistic jets with variability timescales of the order of years (Mattila et al. 2018, RD060, Fig. 4.11). SKA-VLBI will be able to resolve the CCSNe factories in the nuclei of nearby galaxies, up to distances of 100 Mpc, and contribute to population studies of TDEs, resolving and studying their relativistic jets.

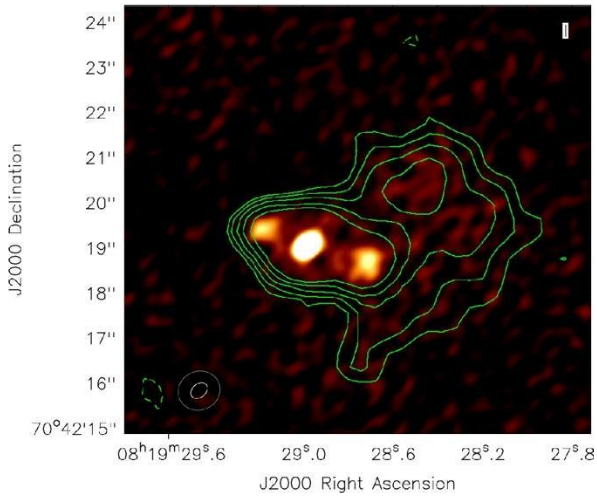


**Figure 4.12. Example of a *ULX source: Holmberg II X-1* (Cseh et al. 2014, RD061)**

Another type of transients is the Ultra-Luminous X-ray sources (ULXs, Fig. 4.12). As *Dr David Williams* explained in its talk ***Energy injection in the ULX Holmberg II X-1*** these sources are now firmly established as super-critical (i.e. above the Eddington limit) accreting sources with the population known to harbour neutron stars and presumably stellar mass black holes. The hyper luminous X-ray sources may yet be candidates for hosting intermediate mass black holes, the link between stellar-mass and supermassive black holes. Such super-Eddington accretion rates are also known to have occurred in the high-redshift universe at the supermassive black holes (SMBHs). Whilst the immense distances to these accreting SMBHs precludes their use as probes of super-Eddington accretion, ULXs are readily observable and can therefore provide insights into the rapidly growing SMBHs and the effect on the high redshift universe.

Different campaigns are ongoing to study ULXs variability, with instruments such as the Arcminute MicroKelvin Imager - AMI (Hickish et al. 2018, RD062) to understand whether the variability is a consequence of repeated ejections rather than the variability of the persistent emission. SKA-VLBI will provide the high resolution and sensitivity to detect and resolve the lobe-core-lobe structure (of the order of 50 microJy/beam) and, with the appropriate cadence

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observations, detect the motions of the ejecta of ~1 mas/month and explain the origin of variability. A SKA key science project will make the case for future observations of radio-bright ULXs with SKA-VLBI to further investigate super-critical accretion in a larger number of sources.

## 4.3 Pulsars and Fast Radio Bursts

Radio astronomy is nowadays able to explore the dynamic universe on timescales of milliseconds thanks to the recent development of sensitive, high time resolution instruments. The talks in this session reviewed the latest results on millisecond transients and their applications.

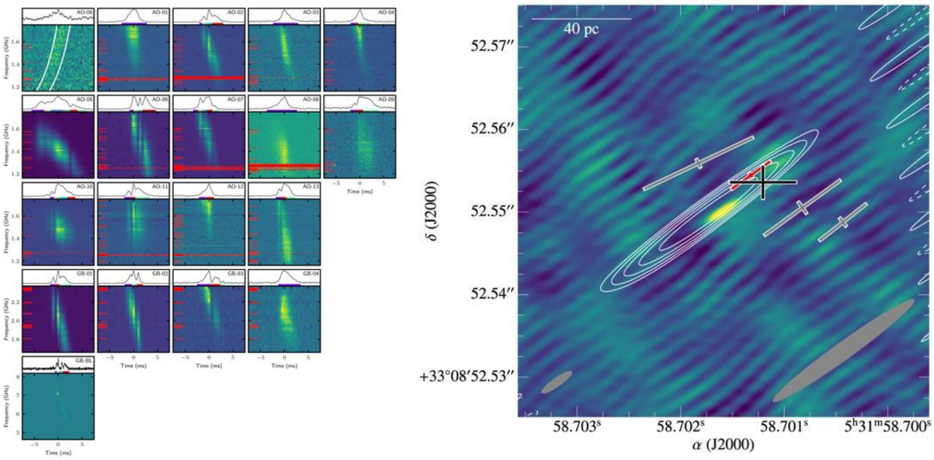


**Figure 4.13. Left: FRB121102, the first FRB repeater (Hessels et al. 2019, RD063); Right: EVN image of the persistent source at 1.7 GHz (white contours) together with the localization of the strongest burst (red cross), the other three observed bursts (gray crosses), and the position obtained after averaging all four bursts detected on 2016 September 20 (black cross) (Marcote et al. 2017, RD064)**

Fast radio bursts (FRBs) are one of the most intriguing puzzles of the decade. They are very bright millisecond duration pulses, mostly coming from the extragalactic sky, without a statistically significant counterpart yet observed. *Dr Manisha Caleb* reviewed the latest findings in the field in her talk ***Fast Radio Bursts with VLBI*** and described how the next-generation telescopes will be vital in the quest to understand this enigmatic population.

The FRB class encompasses a number of single pulses, each unique in its own way, hindering a consensus for their origin. The key to demystifying FRBs lies in discovering and localising many of them in order to identify commonalities. Despite rigorous follow-up of the discovered FRBs, only about 2% have been seen to repeat, suggesting the possibility of there being two independent classes (Fig. 4.13). Alternatively, sensitivity limitations in the detectors could hinder the detection of very faint pulses, only detecting the bright tail end of the pulse energy

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distribution. A collaborative effort between theorists and observational astronomers to explain these phenomena is going on. The most popular theories are flares from magnetars, giant pulses from extragalactic pulsars, binary neutron star mergers or AGN interactions.

The SKA precursors ASKAP and MeerKAT are already excellent instruments for pulsar and fast transient science. Complementary, VLBI provides source localisation at unprecedented precision, essential for most cosmological applications and to comprehend the local FRB environment and progenitors. The future SKA-VLBI will target nearby repeaters and high-z FRBs with its high sensitivity. To make the most of the capability, SKA-VLBI should accept VOEvent triggers from the SKA and external facilities to observe during the active phase of the repeaters. This will certainly represent a challenge for current operational VLBI networks.

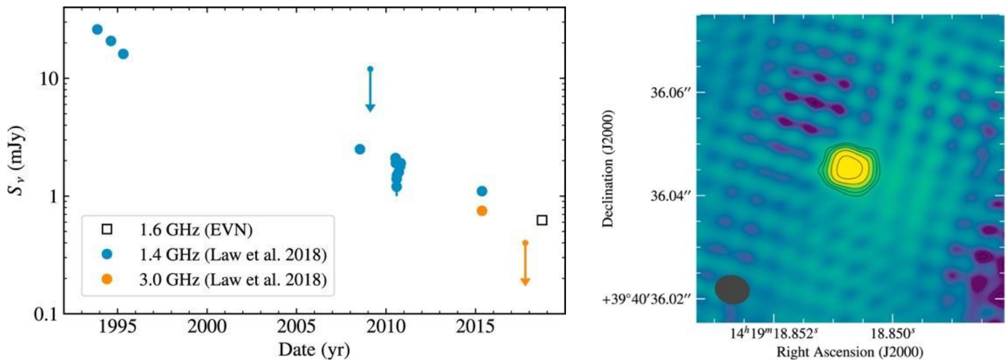


**Figure 4.14. Left: Light-curve of FIRST J1419+3940 during the last 25 yr at 1.4–1.6 GHz (blue circles and open square) and 3.0 GHz (orange circles). Right: Image of FIRST J1419+3940 at 1.6 GHz with the EVN (Marcote et al. 2019, RD066)**

In a search for repeating fast radio bursts in the FIRST radio catalog (Ofek 2017, RD065) a very interesting transient source was found, as highlighted by *Dr Benito Marcote* in his talk ***Resolving a decades-long transient: a possible connection between am orphan long GRB afterglow and FRBs.*** FIRST J1419+3940 is a transient source that has been decaying in brightness over the last few decades (Fig. 4.14). One possible interpretation is that this source is a nearby analogue to the repeater FRB 121102 and that the radio emission represents a young magnetar nebula. Another interpretation is that FIRST J1419+3940 is the afterglow of an ‘orphan’ long gamma-ray burst (GRB). The environment is similar to where most such events are produced. To distinguish between these hypotheses, high angular resolution observations with very good sensitivities and image fidelity are needed.

Observations with the European VLBI Network at 1.6 GHz spatially resolved the non-thermal emission of this mildly relativistic expanding source and unfruitfully searched for millisecond-duration radio bursts. The source properties and lack of short-duration bursts are consistent with a jet expansion from a putative orphan long GRB, whereas they disfavour a magnetar birth nebula.

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SKA-VLBI will contribute to the study of similar transients providing milliarcsecond resolution and high sensitivities needed to detect and resolve them. The full SKA will be able to observe the afterglows for almost the whole GRB population (Ghirlanda et al. 2013, RD067) and deep SKA all-sky surveys may detect around ~100 orphan afterglows per week (Burlon et al. 2014, RD068).

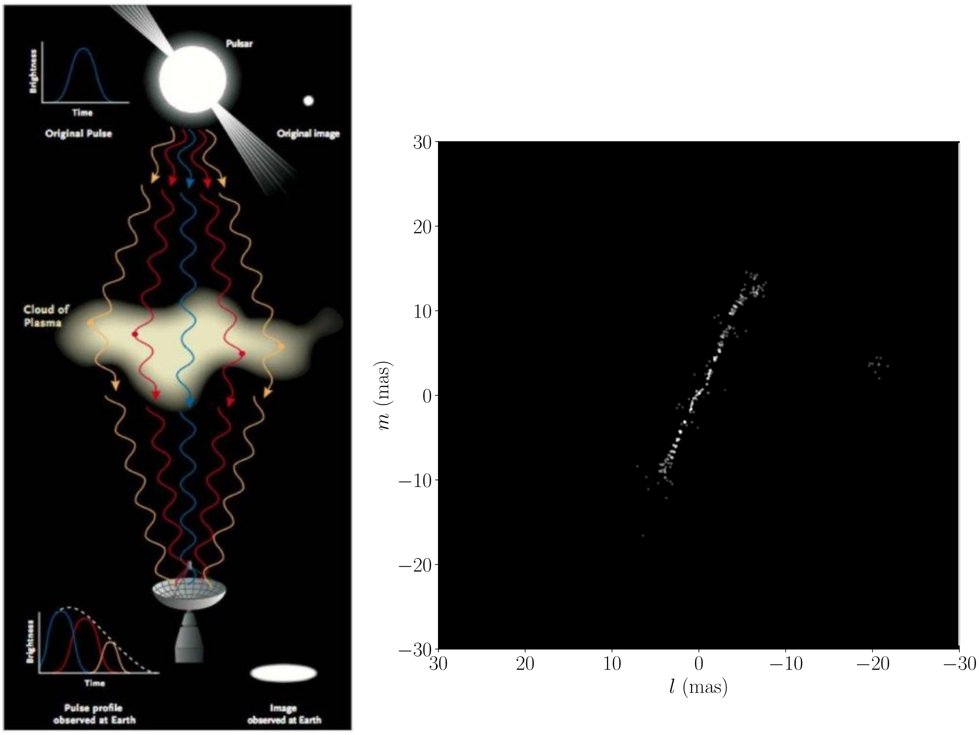


**Figure 4.15. Left: principles of pulsar scintillometry, Haggard & Bower 2016 (RD069); Right: reconstructed scattered image of the pulsar PSR B0834+06 (Simard et al. 2019, RD070)**

Two talks in this session were devoted to pulsar scintillometry (Fig. 4.15). Interferometric pulsar scintillation studies not only illuminate the plasma structures that scatter radio emission but also facilitate studying pulsar emission regions with unprecedented spatial resolution using the plasma as a lens (Brisken et al. 2010, RD071). *Dr Dana Simard* explained in her talk ***Pulsar scintillometry with SKA-Low VLBI*** that to achieve both of these goals, high-sensitivity, wide-bandwidth, and multi-band VLBI campaigns are essential. In particular, the resolution of the interstellar plasma lens is best at low frequencies, where the scattered disk of the pulsar extends furthest from the line of sight. But at these frequencies, the complex scattering environment makes inferring the plasma lens geometry difficult. Interferometric observations at GHz frequencies, where scattering is simpler, may help disentangle the scattering environment.

VLBI observations with the SKA will further the field. VLBI with SKA1-Mid will allow mapping the interstellar scattering screens responsible for the scintillation to determine their

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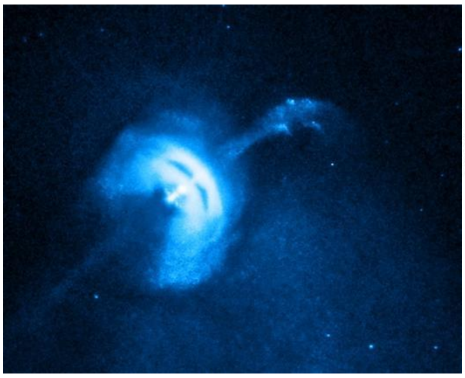
distribution and association with other structures in the ISM. VLBI with SKA1-Low will be able to resolve the pulsar magnetospheres, constraint pulsar beam models and study the transverse motion in binaries.

Different SKA-VLBI observing strategies were outlined. For the lower frequencies, only a few sensitive VLBI baselines will be needed due to the anisotropy of the scatterer. For the mid-frequencies the usage of VLBI and SKA subarrays observing different frequencies to cover larger bandwidths will contribute to better characterisation of the dynamic spectrum, that is sensitive to screens at different distances. To complement these studies, accurate distances to the pulsars need to be determined using astrometric techniques with SKA-VLBI.

These studies will aid in separating the effects of plasma scattering from intrinsic properties of the source and other propagation effects, and may even allow the removal of scintillation, a source of noise of growing importance in highly sensitive, wide-bandwidth pulsar timing observations.



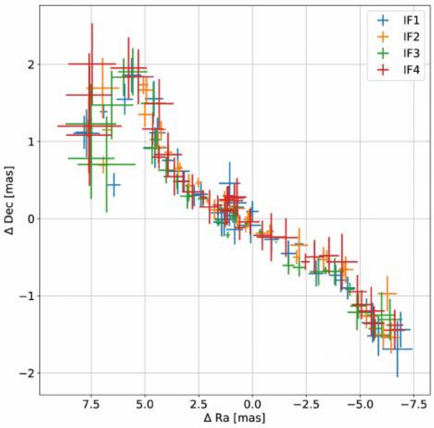



**Figure 4.16. Left: X-ray image of the Vela pulsar (NASA/CXC/Univ of Toronto/Durant et al., RD072); Right: Speckle image of the Vela pulsar (Kirsten et al. 2018, RD073)**

*Dr Franz Kirsten* showed in his talk ***Mapping the scattering screen of the Vela pulsar*** the second-ever speckle image of a pulsar. The ionized interstellar medium scatters the spatially coherent signal of pulsars, leading to multi-path propagation evident as scintillation in the observer's plane. In a dynamic spectrum, i.e. the flux density distribution as a function of frequency and time, scintillation becomes apparent as a criss-cross pattern of intensity variations. In the 2D power spectrum of the dynamic spectrum – the so-called secondary spectrum – the power is distributed along a parabola through the origin. The curvature and shape of this parabola give us insights into the distance of the scatterer and the level of anisotropy in the scattering medium. If observed with VLBI, one can use the phase information in the secondary spectrum to map out the scattering screen. Combined with the distance to the scattering screen, this map can be used to perform high precision astrometry of the pulsar

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itself. Resolving the pulsar magnetospheres or the orbits for pulsar binaries and parallax measurements are the immediate scientific applications.

Long Baseline Array observations of the bright and strongly scattered Vela pulsar at 1.6 GHz detected the parabolic structures in the secondary spectra of both visibility amplitudes and phases (Fig. 4.16, Kirsten et al. 2018, RD073). Whilst using a VLBI interferometer provides no better than 20 mas beamsize, the huge scattering interstellar interferometer has an equivalent beam size of ~250 nanoarcseconds (nas), corresponding to resolutions of the order ~70 nas from Earth and sizes at the distance of Vela of ~3000 km. These observations allowed the determination of the distance and orientation of the scattering screen.

The VLBI capabilities of the SKA will push the relatively young field of pulsar scintillometry forward, providing the necessary sensitivity to reach fainter populations. SKA-VLBI broadband scintillometry will constraint the models of the ISM geometry and will determine the temporal evolution and frequency dependence of the location of the speckles. Simultaneous observations of the VLBI networks with SKA1-Low and SKA1-Mid at bands 1, 2 and 5 will require broadband receivers, the usage of several subarrays and the development of the VLBI capabilities at ~200 MHz for more antennas.

## 4.4 Stellar Science and Astrometry

Formation, evolution and death of the stars can be studied by means of maser emission of different emitting molecules such as hydroxyl, methanol, water, etc. The strong amplified maser emission traces very compact regions where stringent physical conditions are met for the maser to be produced. This emission is ideally studied and resolved with the high angular resolutions provided by VLBI. Apart from stellar science studies, the masers are also used as candles to measure distances, relative positions and proper motions, with astrometric applications in our Galaxy and beyond. As mentioned by the speakers of this session, the sensitivity of the SKA-VLBI capability will expand the current census of maser sources, reaching further distances to cover most of our galaxy, surpassing the Gaia observable zone. New phase-referencing techniques that take advantage of the multiple beams of the SKA-VLBI capability will reduce the systematic errors to the limit to achieve ultra-precise astrometry. The SKA-VLBI sensitivity will also allow the detection of the faint continuum emission produced by high-energy processes in young stellar objects and ultracool dwarfs.

The SKA world's largest telescope will open a new era in astronomy. It will cover frequencies ranging from 50 MHz up to possibly 24 GHz with its unrivalled sensitivity. *Dr Yoon Kyung Choi* stressed in her talk ***Stellar maser astrometry with SKA-VLBI***, that SKA together with the VLBI will be the most powerful tool for the astrometry thanks to the new phase-referencing techniques, such as MultiView (Rioja et al. 2017, RD021), that will allow ultra-precise astrometry down to ~1 µas accuracies. Stellar maser astrometry will mainly focus on OH and water masers, increasing the number of target sources in current surveys (Engels & Bunzel

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2015, RD074; Beuther et al. 2019, RD075; Dawson et al. 2014, RD076). Astrometric measurements such as distance and proper motions are crucial to calibrate stellar fundamental properties and compare them with the Gaia mission results (Fig. 4.17). Xu et al. 2019 (RD079) has shown that circumstellar masers for AGB stars can yield to parallax accuracies an order of magnitude better than on Gaia DR2.

Synergies of SKA-VLBI with Gaia and ALMA observations are also expected to shed light on the inner structure of the Galaxy and its bulge, expanding the BAaDE survey (Pihlström et al. 2018, RD080), and reaching further away, complementing the GASKAP survey of HI, OH and masers in the Magellanic Clouds (Dickey et al. 2013, RD081).

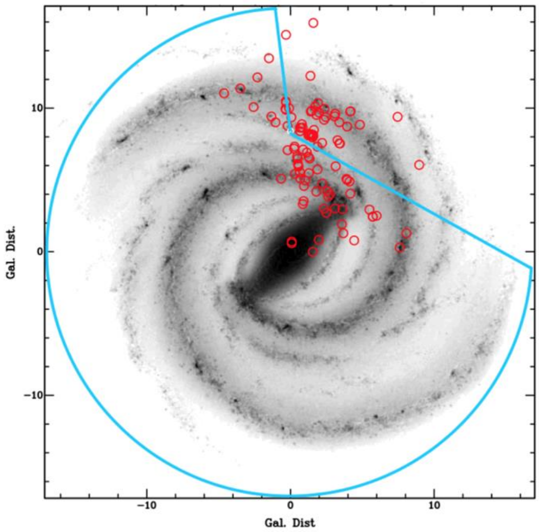


**Figure 4.17. Masers (red circles) with astrometric parallaxes from the BeSSel survey (Reid et al. 2014, RD077), showing the galactic region accessible with SKA-VLBI (blue line) (Green et al. 2014, RD078)**

***Mass loss from evolved stars is fundamental to the enrichment of the ISM*** as highlighted in *Dr Anita Richards'* talk. The region within a few stellar radii is subject to stellar pulsations, crucial to mass loss both directly, and indirectly, by affecting the chemistry. Further out, shocks arise from wind interactions. The exponential nature of maser amplification allows the emission to be measured on scales an order of magnitude finer than possible when observing thermal lines. VLBI and e-MERLIN have long been used to resolve SiO and water masers, at wavelengths of 1.3 cm and shorter, showing how complex outfall and infall nearer the star changes to outward radial acceleration once dust is fully formed (De Beck & Olofsson 2018, RD082). More than half the mass loss appears to be concentrated in clumps with less than 1% filling factor. Global mass loss estimates (e.g. from CO or dust) cannot be made accurately unless this factor is accounted for, and the heterogeneous conditions may also affect the local chemistry (Fig. 4.18, Richards et al. 2012, RD083).

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Hydroxyl maser 'mainlines' at 1665/7 MHz appear to trace the low-density inter-clump gas in the outer water maser regions, surrounded by 1612 MHz OH masers, but e-MERLIN's maximum baseline of 217 km does not provide astronomical unit resolution at these wavelengths. On the other hand, a high proportion of flux is resolved out unless baselines $\lesssim$100 km can be included.

The power of SKA in VLBI will provide a unique combination of advantages: high resolution for highly-beamed sub-mas spots; sensitivity to weaker, more extended emission; the capability to detect the star itself; and the overlap with ALMA's sky. One of the many possibilities this opens up is the direct measurement of maser beaming, which has different characteristics if the emitting regions are quiescent clouds or shocked slabs. The clumping scale and internal motions can be tracked, and fractal analysis can also be used to investigate turbulence. These techniques can also be used to study star formation and other maser environments.

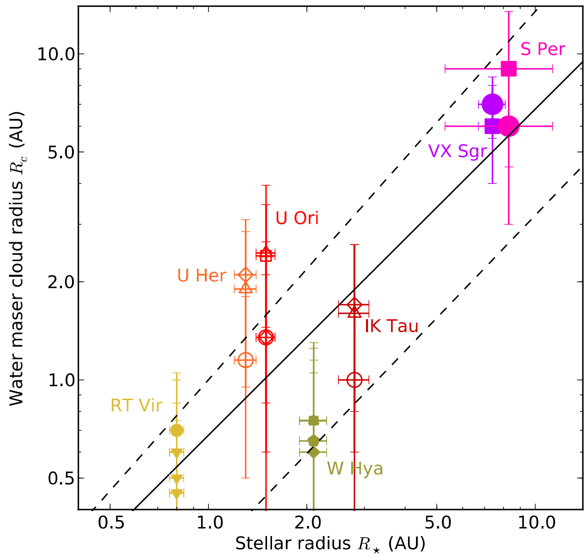


**Figure 4.18. The plot shows that the size of the water maser clouds, $R_c$, is determined by the size of the star, $R_\star$, for a sample of variable stars (Richards et al. 2012, RD083).**

*Dr Sandra Etoka* deepened on the ***Structural changes of stars at the dawn and dusk of their evolution.*** Ground-state OH maser emission is the most common maser emission emanating from the surrounding material of both young stellar objects and evolved stars. SKA surveys will allow the discovery of many new sources, in particular low-luminosity maser emitters (Etoka et al. 2015, RD084). This will enable the census and study of these maser-emitters throughout the Galaxy, in particular in the anti-solar Galactic hemisphere, providing us with a more complete picture of our own galaxy.

While part of this emission can be of extended nature sometimes observed towards standard and relatively close-by OH/IR stars or as a low-level emission in some star forming regions (SFRs), the bulk of this emission is of compact nature and sometimes strongly polarised. The

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compact emission is typical in SFRs (Argon et al. 2003, RD085; Sanna et al. 2015, RD086) and for a subclass of evolved stars in flaring and transitional stages, such as the OH maser emission in the early Planetary Nebulae stage or towards post-AGB stars and possibly red supergiants (Fig. 4.19, Etoka et al. 2017, RD087; Gomez et al. 2016, RD088).

Both the sensitivity and resolution of SKA-VLBI is needed for the study of such compact and faint emission, key in the understanding of the geometry and associated magnetic field structural changes undergone by stars in these early and late stages of their evolution.

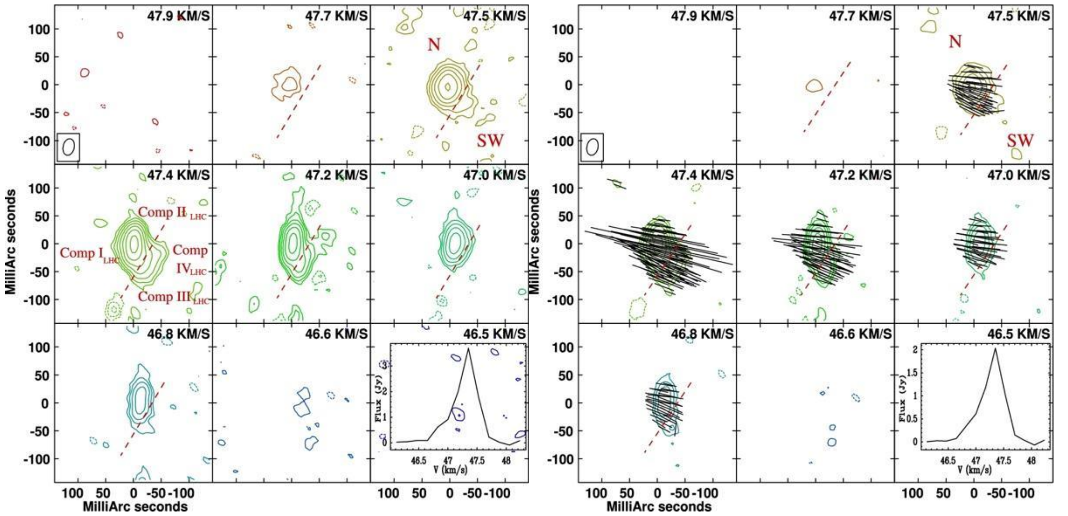


**Figure 4.19. Mira O Ceti OH emission detected in EVN and e-MERLIN observations (left) and polarimetric information (right), Etoka et al. 2017, RD087.**

In recent years, high-energy processes in young stellar objects (YSO) have largely been studied using X-ray observations. While it has been known for some time that radio observations provide complementary information on coronal activity, high-energy irradiation of both protoplanetary disks and planets, mass accretion, and jet formation, it is only now, with unprecedented observational capabilities, that we can systematically obtain this information. The connection between radio and X-rays and the time domain studies also contributed to the discovery and study of ultracool dwarfs (UCDs, Berger et al. 2001, RD089; Forbrich & Berger 2009, RD090).

To demonstrate these observational capabilities, *Dr Jan Forbrich* presented the talk ***Young stellar objects and ultracool dwarfs*** with results of radio surveys targeting the Orion Nebula Cluster (ONC), using the upgraded VLA and VLBA as well as ALMA, partly with simultaneous Chandra observations (Forbrich et al. 2017, RD091). The deep VLA and Chandra observations have enlarged the sample of known radio sources in the ONC by a factor of more than 7, enabling detailed comparisons of X-ray and radio YSO populations while providing the first systematic set of simultaneous YSO radio and X-ray lightcurves. With these data, one can look into the detailed correlation of X-ray and radio flares from YSOs, including radio spectral index

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information. Precision astrometry with the upgraded VLBA allowed high-resolution follow-up of all VLA detections in one pointing, reaching 10x deeper and detecting 100x more sources. Annual monitoring of absolute proper motions is sensitive to motions of 0.1-1 km/s, a level at which everything moves (Fig. 4.20, Forbrich et al. in prep, RD093).

Overall, these results highlight a new perspective on high-energy processes in YSOs and UCDs. The SKA-VLBI capability will allow follow-ups of the lower-resolution radio detections in future SKA surveys. It will also provide measurements of parallaxes and absolute proper motions of faint stars that Gaia cannot detect and will contribute to astrometric cross-checks for a small overlap of bright nebulae and embedded objects. Other applications are searches for exoplanets, detection and orbit determination of binaries and direct searches for large magnetic structures.

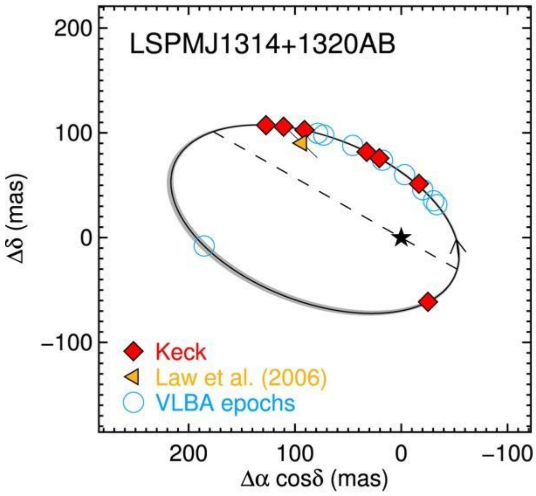


**Figure 4.20. Multi-epoch astrometry of a young ultracool dwarf binary (Dupuy et al. 2016, RD092).**

Astrometric studies of maser sources using VLBI provide unique measurements of the Galactic distribution of both very young and evolved stars. Because radio observations are not affected by interstellar extinction, such measurements continue to be of fundamental relevance even when precise Gaia astrometry is available; perhaps even more so (Fig. 4.21). *Dr Huib van Langevelde* reviewed the different astrometric efforts in his talk ***Galactic structure through maser astrometry with VLBI@SKA***. Distances to individual objects calibrate the astrophysical processes in terms of luminosities, accretion and mass-loss rates, central object masses, etc. They also provide a tie for observations performed at different wavelengths. By studying many targets in the galaxy one can try to answer how the galaxy was formed and how it evolves, deduce recent and ongoing mergers, deduce the spiral type and size, total mass, dark matter content, star formation rate and history, and understand the stellar populations, evolution and their distribution.

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Current VLBI astrometry is limited by a number of factors to an accuracy no better than ~10 µas. The accuracy depends on the baseline length and the SNR of the detection, which in turn depends on the strength of the maser, collecting area of the network, number of epochs and integration time, and observing bandwidth. But the accuracy is mostly dominated by systematic errors, such as how accurate one can measure phase differences using nearby calibrators, how good the models of the different atmospheric propagation effects are, the timing accuracy, the correlator geometric model and telescopes positions accuracy, etc.

The BeSSel survey (Reid et al. 2014, RD077) is based on observations of young massive stars mostly at methanol but also based on many individual projects at other frequencies. It has provided the best way to measure the Milky Way parameters, bias-free, and has been unique for localising the spiral arms (Reid et al. 2019, RD095). Recent results show that the spiral arms have few kinks (Quiroga-Nuñez et al. 2019, RD096). Southern VLBI predicts a theoretical improvement on the basic galactic parameters, notably for the inner structures, the bar and molecular ring (Green et al. 2011, RD097; Krishnan et al. 2015, RD098).

The BAaDE project (RD080) uses evolved stars as targets. It first observed OH masers that are restricted to < 1kpc due to limited brightness. Later results with water masers and VERA interferometer improved considerably. Studies using SiO masers are harder but there are many bright sources providing higher resolutions. SiO velocity measurements with VLA and ALMA have shown bulge asymmetries and dynamic evolution (Sjouwerman et al. 2018, RD099). VLBI SiO astrometry has serious limitations (short coherence times for cross-calibration, few and weak calibrators, SiO masers are close to the stars and variable, with a-priori positions poor, etc.) that could be overcome with more complete calibrator surveys, explore non-imaging astrometry, consider K/Q cross-calibration, implement new methods, etc.

SKA-VLBI will provide higher SNR detections in the south and many more nearby calibrators, that can be targeted with independent beams for in beam MultiView (Rioja et al. 2017, RD021) to solve for the atmosphere and improve observing efficiency. Therefore, the high sensitivity of VLBI observations with SKA1-Mid in the network will not only improve the noise characteristics but will also allow reducing the systematic errors when measuring parallaxes and proper motions.

Maser astrometry with SKA-VLBI will access the obscured parts of the Galaxy, where Gaia or Jasmine cannot access and will benefit from a flexible VLBI configuration, specific software and algorithms, high-frequency receivers, more SKA1-Mid compatible VLBI stations and lots of observing time by means of commensal observing.

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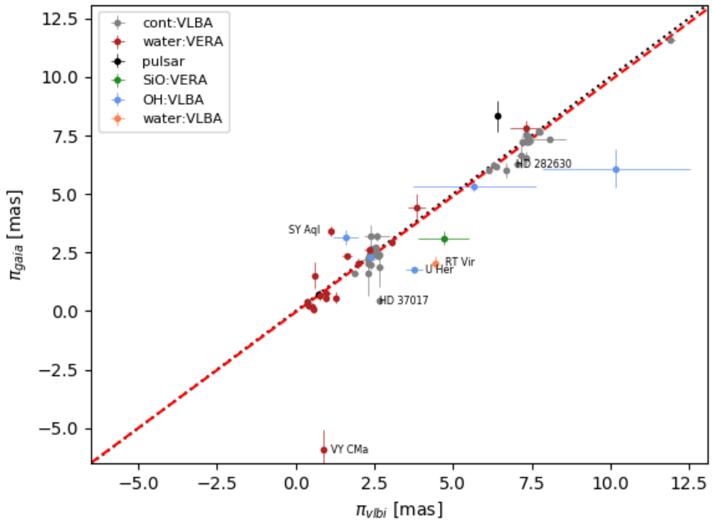


**Figure 4.21. Gaia DR2 versus VLBI parallaxes with comparable accuracies but results with water masers still win (van Langevelde et al. 2018 from many sources, RD094 EVN Symp).**

To finish the session *Dr Hideyuki Kobayashi* gave the talk ***Cradle of Life Science with SKA and VLBI networks in East Asia*** on behalf of Dr Tomoya Hirota**.** Mizusawa VLBI Observatory of NAOJ has been discussing possible science cases of SKA-VLBI as a future plan of VLBI networks in Japan and the East-Asian region (Fig. 4.22). As a result, a report was published in 2017 and a SKA study group was established in April 2018. One of the highlighted science cases was the study of stellar radio emission associated with young stellar objects and pre-main sequence M-dwarfs stars (Forbrich and Berger 2009, RD090) which are hardly detected by the currently available VLBI networks. Planet search through VLBI astrometry (Bower et al. 2011, RD100) will also be possible using the SKA-VLBI capability.

A future array configuration in the southern hemisphere would expand VERA and the KVN within the EAVN, including new 40, 70 and 100 m-class antennas in Asia, as well as FAST, Parkes, and both phased instruments ASKAP and ATCA. Hence, it looks feasible to expand the High Sensitivity Array (HSA) towards the south, with the availability of possibly more than two 100 m-class antennas at a time. Compatibility issues in terms of common frequencies and bandwidths will need to be sorted out. SKA-VLBI will improve the sensitivity of this network down to <10 µJy. The preparatory study can be started using the EAVN with a more detailed estimation of the capability using a realistic array. There is also interest in developing a lower-frequency array (<2 GHz) in East Asia, given the importance of future collaboration with FAST, ASKAP and SKA1-Low.

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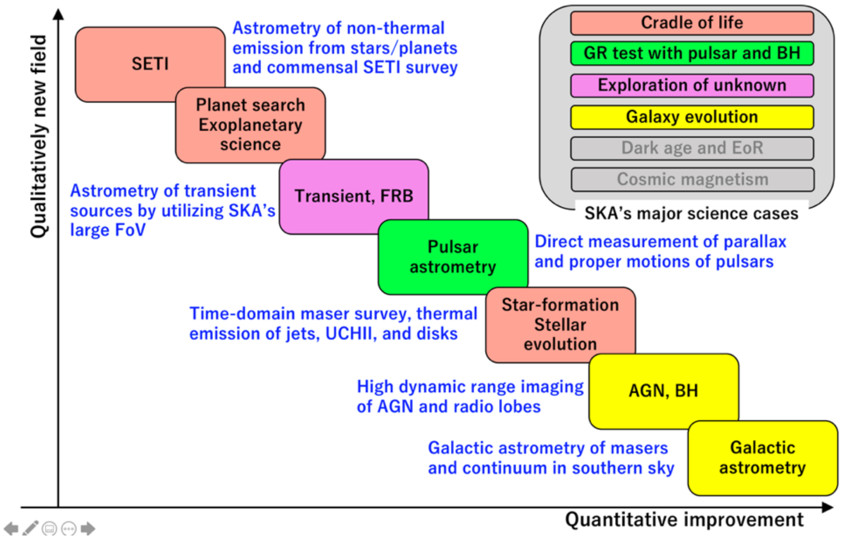


**Figure 4.22. NAOJ SKA-VLBI science cases.**

## 4.5 Prospects for the SKA-VLBI capability

This session approached different aspects of the SKA-VLBI capability: Cosmological applications using strong gravitational lenses, promising SKA-VLBI science data challenges, involvement of the VLBI networks, particularly the Australian LBA, in the success of the capability, finishing with the SKA-VLBI science opportunities that the potential SKA band 6/7 upgrade will bring.

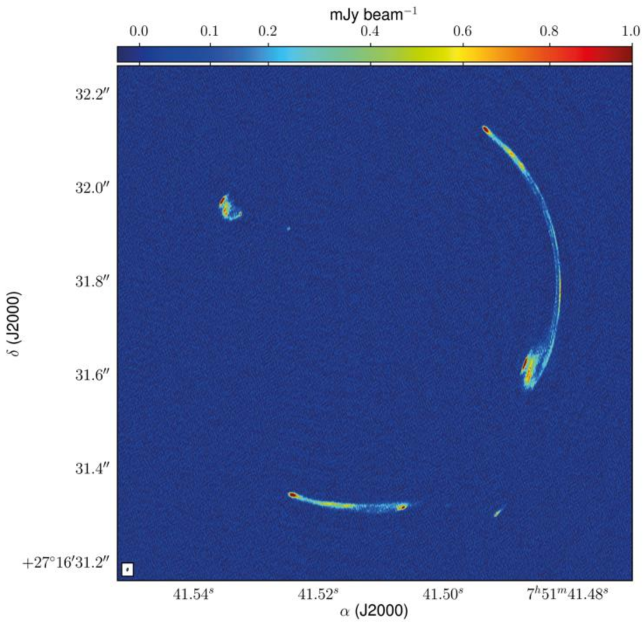


**Figure 4.23. Global VLBI imaging of gravitationally lensed radio source MG J0751+2716 at 1.65 GHz (Spingola et al. 2018, RD101).**

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Strong gravitational lenses (Fig. 4.23) provide an important tool to measure masses in the distant Universe, thus testing models for galaxy formation and dark matter and dark energy; to investigate structure at the Epoch of Reionization; and to measure the Hubble constant and possibly '*w*' as a function of redshift.

However, *Dr John McKean* outlined in his talk ***Testing models for dark matter and dark energy with SKA-VLBI***, that the limiting factor in all of these studies has been the currently small samples of known gravitational lenses (~$10^2$). The era of the SKA will transform our understanding of the Universe with gravitational lensing, particularly at radio wavelengths where the number of known gravitational lenses will increase approximately three orders of magnitude.

In addition, the capability to carry out VLBI with the SKA1 is required to make use of gravitational lensing for tests of dark matter and dark energy and studies of supermassive black holes at high redshift, in wide-field surveys. The success of the technique is reliant on sufficient sensitivity, frequency coverage and dynamic range.

It will be important to engage with the SKA community to show the benefits of SKA-VLBI for the science cases, and with the wider astronomical community to demonstrate the synergies that will be possible with ELT and ALMA.

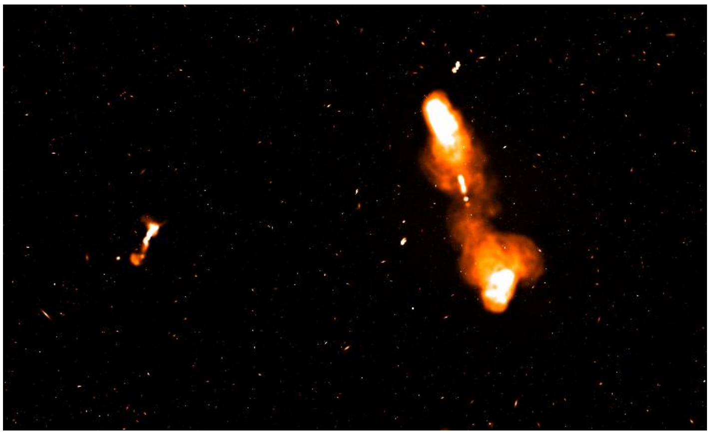

**Figure 4.24. A snapshot from the SKA Science Data Challenge image, showing a large Active Galactic Nucleus (AGN) as if observed by SKA-Mid at 1.4 GHz (Credit: SKA Organisation).**

The SKA Observatory will regularly issue Science Data Challenges to the community as part of the science preparatory activities. *Dr Anna Bonaldi* explained in her talk ***The SKA data challenge*** that the purpose of these challenges is to inform the development of the data reduction workflows, to allow the science community to get familiar with the standard products the SKA will deliver and to optimise their analysis methods to exploit the rich scientific value of the data.

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The first science data challenge (SDC1, Bonaldi et al. 2021, RD102) consisted of a SKA1-Mid continuum simulated observation, covering three frequencies (560 MHz, 1400MHz and 9200 MHz) at three depths (8 h, 100 h and 1000 h), confusion limited but with a benign SKA dirty beam (Fig. 4.24). Participants were asked to apply source detection, characterization and classification methods to the simulated data. The results demonstrated the variety of approaches that can be successfully used in a deep, crowded field and showed the importance of building domain knowledge and expertise on this kind of analysis to obtain the best results.

The author surveyed the audience for a potential SKA-VLBI science data challenge that would target the VLBI community. Three options were given:

1. a SKA-only data product, to investigate survey strategies and target selection, delivering SKA SRC images or catalogues,
2. a VLBI product w/wo SKA data, to demonstrate SKA as a VLBI element, delivering VLBI imaging products,
3. a VLBI dedicated simulation, to investigate a specific aspect of the VLBI data analysis, delivering raw VLBI visibilities and SKA imaging of calibrators.

The result of the poll was virtually no votes for option 1, and there was almost a 50/50 split between options 2 and 3, with 3 being the overall preferred option.

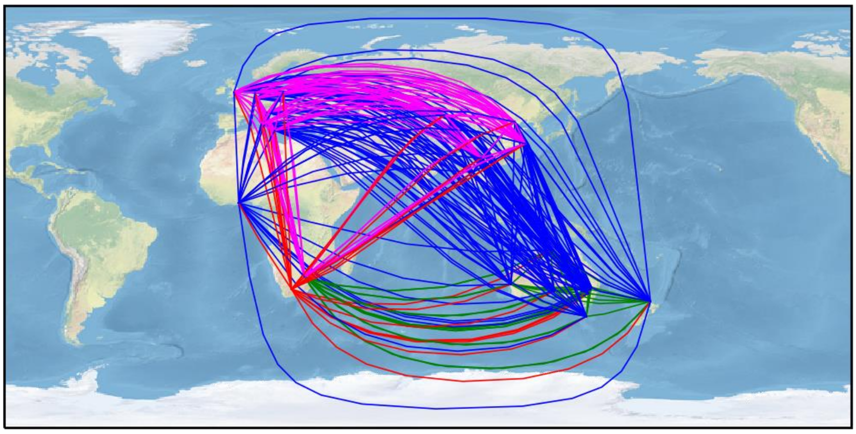

**Figure 4.25. LBA, EVN, EAVN and SKA baselines.**

The Australian Long Baseline Array (LBA) is a partnership between Australia, New Zealand and South Africa that collaborates with the EVN and Asian telescopes. It supports a wide range of galactic and extragalactic science, with astrometry playing a pivotal role for both. *Dr Chris Phillips* introduced the role of ***The Long Baseline Array in the era of the SKA.***

The network is currently undergoing or is planning a number of technical upgrades: ultra-wideband low (700 MHz - 4 GHz) and high (4-26 GHz, planned) frequency receivers for Parkes; the ATCA “BIGCAT” upgrade with 8 GHz bandwidth processing in a GPU backend (planned);

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the ASKAP tied array with multiple beams across 30 sq. degree field (planned in 2 years); and the AuScope geodetic network VGOS compatible wideband receiver (3-13.5 GHz). To develop the LBA further towards the lower frequencies (i.e. LBA-Low), the Bluering project (Hampson et al. 2019, RD103) plans to extend the MWA array to much longer baselines, possibly installing MWA style dipoles at existing LBA observatories or near existing network nodes across Australia.

In the SKA era, VLBI follow-ups will be vital for many areas of SKA science. SKA-VLBI makes the case to retain the existing facilities (telescopes, correlators, etc.) and standards (observing modes, formats, etc.). The LBA role for southern hemisphere SKA-VLBI will be crucial, ideally as part of a global network (Fig. 4.25).

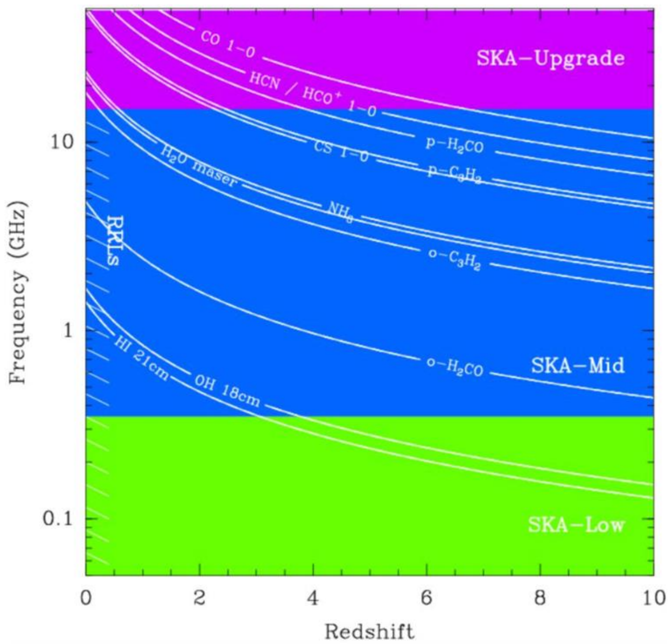


**Figure 4.26. Molecules and redshifts accessible with the SKA Band 6/7 upgrade.**

The SKA is designed for at least a 50-year lifetime. During this time the SKA Observatory Development Programme (ODP) is expected to expand the initial capabilities to enable new categories of transformational science. A possible expansion of SKA1-Mid to higher frequencies is already included as an option in the SKA1 baseline design, at least up to 25 GHz (i.e. Band 6) and perhaps as high as 50 GHz (i.e. Band 7) (Fig. 4.26). *Dr Mark Sargent* explained the details of the upgrade in his talk ***Band 6 for SKA1-Mid.***

The key science cases for including higher frequencies on SKA1 are described in the *Beyond Band 5 White Book* (Conway et al. 2020, RD104). SKA1's wide range of baselines, and its southern hemisphere location, supporting galactic science and providing synergies with ALMA and large optical/IR telescopes, are additional important advantages of a high-frequency SKA1

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compared to other instruments. Moreover, it brings a wealth of SKA-VLBI science opportunities, such as ultra-precise astrometry with water and SiO masers (this workshop, section 4.4).

## 4.6 VLBI in Africa

A very important effort is being accomplished to develop Radio Astronomy in Africa, not only from the scientific perspective but also as a means to benefit the local economies and stimulate economic growth in these countries. The new radio astronomy infrastructures already built or in near construction (e.g. MeerKAT and SKA1-Mid) need to be accompanied by human capital building to better exploit them. Very complete training programs are developing scientific and technical capacity for radio astronomy and VLBI in Africa (JUMPING JIVE WP9 effort).

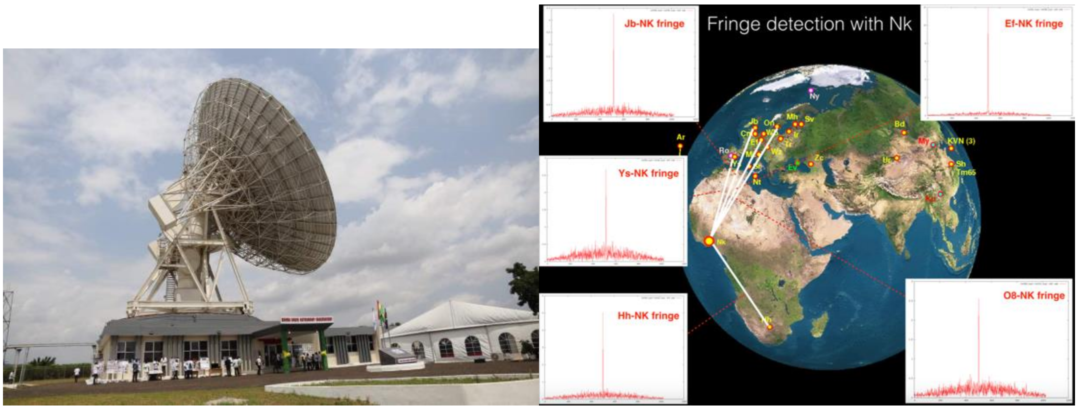


**Figure 4.27. Left: Kuntunse antenna in Ghana; Right: first fringes with the Kuntunse antenna in an EVN observation.**

*Dr James Chibueze* introduced the ***African VLBI Network (AVN): Catching galactic transient events in the SKA era.*** This project aims to develop a network of VLBI-capable radio telescopes on the African continent, to contribute to phase 2 of the Square Kilometre Array (SKA), within 9 African countries, and to further expand the VLBI networks.

The first member of the AVN is the Kuntunse antenna in Ghana, where a considerable effort was performed to refurbish a decommissioned telecommunication antenna (Fig. 4.27). Apart from its future contribution to the EVN observations, already successfully tested, the radio telescope is contributing to the study of galactic transients, such as low-mass young stars (Safron et al. 2015, RD105) and to the follow-up of accretion bursts in high-mass protostars (MacLeod et al. 2019, RD106).

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In the SKA1 era, the number of transient events detected will be several orders of magnitude larger than today. A Flexible VLBI Network (FVN) for galactic transient localisation and follow-up, that would include African and European telescopes available on short notice, will be key to catch these time-limited events.

**Figure 4.28. Left: Swedish-ESO submillimetre telescope decommissioned (Credit: L. Zychova/ESO); Right: Mount Gamsberg in Namibia (Credit: Bernd Schroeter, Regensburg)**

The Africa Millimetre Telescope (AMT) will be a 15-metre mm-wave antenna built on Mount Gamsberg (2347m) in Namibia. The weather conditions, with a yearly average value of 5.2 mm water content, are good for mm-wave astronomy. *Dr Rhodri Evans* announced in his talk ***The Africa millimetre telescope and the AVN*** that it has been decided to use the Swedish ESO Sub-mm Telescope (SEST), which was decommissioned in 2003 in La Silla, Chile (Fig. 4.28). This telescope will be refurbished in France before it is shipped to Namibia. The main receivers will operate at 100 GHz (3mm) and 230 GHz (1.3 mm).

The AMT will be part of the next-generation EHT collaboration. Therefore, the AMT primary scientific goal will be to image the supermassive black hole at the centre of M87 and our own Galaxy, probing general relativistic effects in the strong-field regime and to study accretion and relativistic jet formation near the black hole boundary.

However, they are also considering using the AMT as the antenna for the Namibian part of the Africa VLBI Network (AVN). To do this, the AMT receiver cabin will need to accommodate cm-wavelength receivers, but they are confident that these technical challenges can be overcome. The AMT can be an important link in the AVN, thus enabling Africa to more quickly realise its potential in radio interferometry science.

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# 5 SKA-VLBI Key Science Projects discussions

The possibility to initiate VLBI Key Science Programmes have been motivated by the fact that a number of SKA1-Low and SKA1-Mid highest-priority science objectives depend on, or benefit from very high angular resolution observations; possible SKA-VLBI strategies have been outlined by Paragi, Chrysostomou and García-Miró (2019, see Annex 2, RD107). An important question is what fraction of time the first-phase SKA telescopes will be available for VLBI science (either in KSP or for general observing time), and if competitive science cases can be compiled by the community. Another question is whether the careful organization of SKA resources could allow more time for VLBI observations parallel to SKA projects. In light of the science cases presented by the participants, and the technological capabilities introduced in the presentations during the first day, the scene was set to discuss what is possible to achieve with the known telescope configurations, and how to organize the community in the coming years.

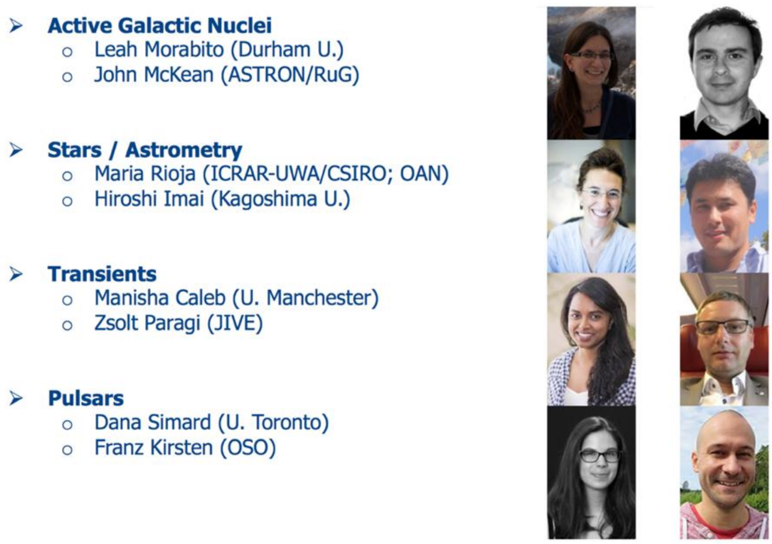


**Figure 5.1. Key Science Projects discussion groups leaders.**

The participants were asked to form KSP groups at the workshop following the major themes of active galactic nuclei (AGN), stars/astrometry, transients, and pulsars. The group leaders are shown in Fig. 5.1. During breakout sessions, these groups discussed the VLBI science cases and possible strategies for VLBI Key Science Projects (KSPs). The group leaders were asked well in advance of the workshop celebration to define the program and lead the discussions. They were also responsible to present an informal summary during the last session. The discussions needed to address the following questions, as many as possible in the short time available, or come up with their own questions, if any:

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- Is the list of SKA-VLBI use cases complete? or are there important science topics missing?
- Are the technical constraints of these SKA-VLBI use cases well understood and presented? (number of beams, aggregate data rates, SKA correlator limitations, calibration requirements)
- How would you prioritise; what should be the main themes?
  (considering that a number of use cases should probably be merged later)
- What commensal approaches might apply?
  (thinking about possible piggy-backing on SKA1 surveys for example, if possible)
- What are the telescopes that are needed
  a) to reach the minimum goals,
  b) for preferred ideal sensitivity and uv-coverage,
  c) for a truly ambitious implementation of the project?
- What multi-messenger synergies should we focus on? (if applicable)

The SKA project scientists were asked to join the discussions and helped with the moderation and answered any SKA-related questions. At the end, three parallel discussions were held, because the transient and the pulsar themes merged. The three groups approached the task in different ways, and they brought a number of interesting ideas.

## 5.1 Active Galactic Nuclei

The AGN science themes are presented in Fig. 5.2. The AGN group has gone through the existing use cases thoroughly (Table 5.1) and came up with an additional 5 new ones (Table 5.2). While it is important to broaden our view and even think out of the box, in the future, it will be very important to narrow down this list to a few, high impact science cases, and work out the detailed science justifications. At the moment some of the use cases are vague – but in this early stage we are still brainstorming, and just ask the question of what direction we should follow.

All the AGN use cases can be classified into 6 Key Science Themes, indicating the unique VLBI capability/ importance:

1. AGN/SF Separation: need resolution to measure brightness temperature
2. AGN feedback/fuelling - HI, OH (1.7 to 12 GHz): VLBI fundamental to resolve sub-galaxy scales / covering factor
3. BH, accretion disk, cosmology ($H_2O$): have to resolve the location of water masers
4. Jet physics (radio-loud/radio-quiet): size scales are milli-arcsec
5. Dark matter – milli-lensing: size scales are milli-arcsec
6. SMBH evolution: size scales are milli-arcsec

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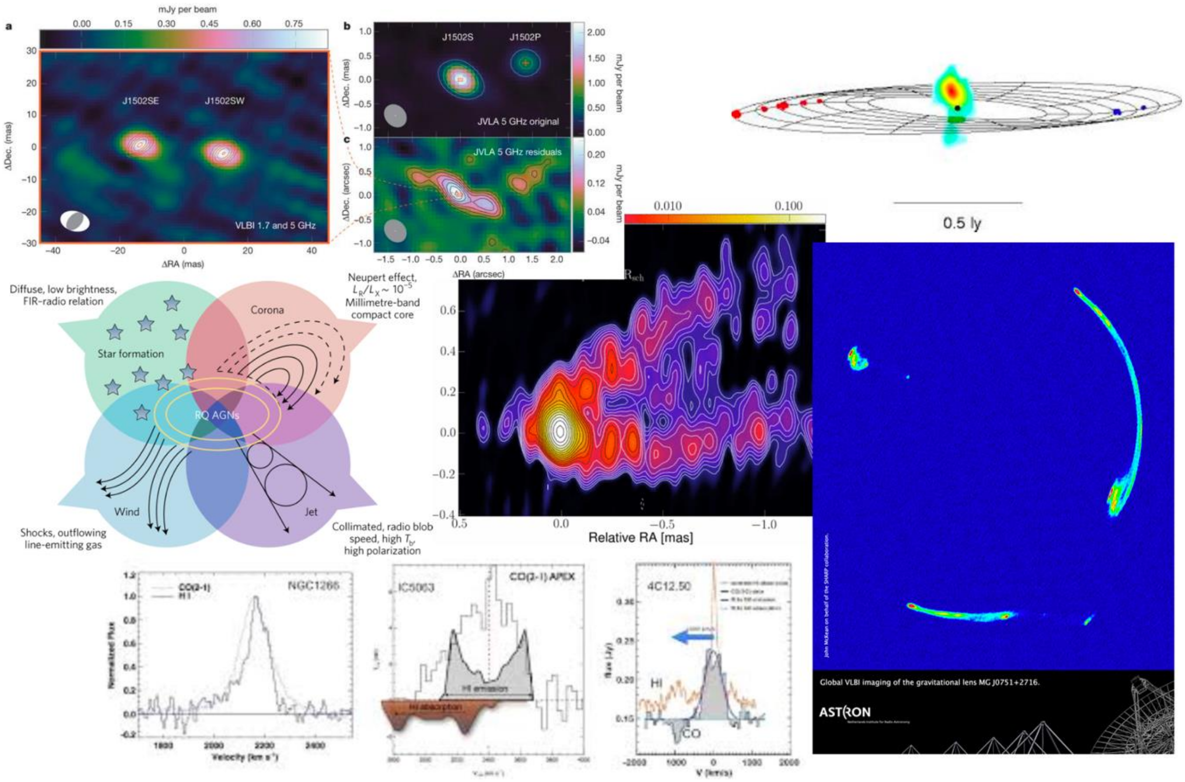


**Figure 5.2. AGN Key Science Themes.**

The group identified the following potential observing modes (dependent on source density):

- Targeted mode — Beam formed (target+calibrators)
- Survey mode 1 — Beam formed (10’s of beams, switch between targets)
- Survey mode 2 — Individual SKA telescopes and Beam formed
- Survey mode 3 — VLBI correlator on-site, producing 1000’s beams and transfer the global array data to SKA

Science cases 2, 4, and 6 can be done in targeted mode, whilst science cases 1 and 5 can be done in any of the survey’s modes (1, 2 and 3). In the particular case of science case 3, it would need a wide-field high-frequency survey.

The issue of commensality was highlighted in the discussions:

- All the science cases can potentially be carried out during SKA surveys
- It would be more effective to piggy-back surveys on VLBI scheduling

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**Table 5.1. Existing AGN Use Cases**

| | | |
|---|---|---|
| HI absorption at sub-kpc scales in normal and active galaxies at high redshifts | HI-ABS-(LOW) | Gupta |
| AGN Physics at very low frequencies in COSMOS | AGN-(LOW) | Morabito |
| Adding high angular resolution to SKA surveys through wide-field-VLBI technique | WIDEF (MID) | Giroletti |
| A Deep Multi-Frequency VLBI Polarimetric Survey of a Big AGN Sample | AGN-SUR (MID) | Agudo |
| Chasing Merged and Merging Supermassive Black Holes | BSMBH (MID) | Anton |
| Dark matter, and investigating the high redshift Universe with strong gravitational lensing | SGRAVL (MID) | McKean |
| Intermediate-mass black holes | IMBH (MID) | Mezcua |
| Characterising feeding and feedback in high-z radio AGN using HI absorption with SKA1-MID | HI-ABS-(MID) | Morganti |
| Extremely high-redshift AGN with SKA-VLBI | HIGHz-AGN (MID) | Perger |

**Table 5.2. New AGN Use Cases**

| | | |
|---|---|---|
| OH Absorption line survey (1.7 - 12.2 GHz) | OH-ABS (MID) | |
| H20 Megamasers (22.2 GHz) | H20-EMIS (MID) | |
| Monitoring jets (various scales) | JETS-MONITORING | |
| 3C/4C sources | 3C | |
| Local low power AGN | GATOS-(MID) | |

The group has established that sensitivity, uv-coverage, dynamic range and image fidelity are all important requirements for the science cases. The imaging capability will not only depend on uv-coverage, but we must understand the point-spread-function (PSF) of the SKA1 telescopes. In this regard, simulations are necessary to determine what is really needed. A possibility of forming a SKA-VLBI simulations working group has been mentioned. Finally, since the VLBI imaging capability strongly depends on the availability of intermediate baselines, the need for additional stations in Africa and Australia has been highlighted.

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The actions taken by JUMPING JIVE WP10 and collaborators to address these points are detailed in Section 6, but here are some in advance remarks. The “Targeted mode” will be available by default. But it has to be noted that the other observing modes have issues. ”Survey mode 3” is not compatible with the current SKA1-Low/Mid design. It requires recording voltage data for all SKA telescopes, for an extended period of time, which would put significant stress on SKA resources. It would also require a very capable VLBI software correlator installed on-site that would, as well, receive the data from the global array telescopes, requiring a broadband internet connection. “Survey mode 1” is only possible by introducing subarrays, thus compromising sensitivity per beam.

“Survey mode 2”, which implies phasing up the SKA core plus using additional, individual SKA dishes was a new idea at the workshop. This mode has various advantages. The SKA core will provide substantial sensitivity, but it is also expected to provide data products (derived from interferometry images) that could be bootstrapped for very accurate calibration of the VLBI data. SKA imaging in parallel to VLBI beamforming of the core will however not be possible at 5 GHz or higher frequencies (SKA Band 5 and higher) at the standard SKA frequency resolutions. Adding a number of individual SKA outrigger dishes to the array would provide the short spacing for observing primary flux and polarization calibrators and thus have all the necessary information for calibration self-contained in the VLBI dataset. Therefore, the JUMPING JIVE WP10 team decided to support the implementation of this observing mode and included it in an Engineering Change Proposal (ECP, see Annex 3) that was primarily addressing the maximum number of 4 VLBI beams in the Design Baseline, which is not sufficient (see Sect. 6.2). This ECP has been approved by the SKA Project. Although it is yet to be implemented during the different construction phases, this is a major success for SKA-VLBI and JUMPING JIVE WP10 in particular.

## 5.2 Stellar Science and Astrometry

The main stellar targets for SKA-VLBI are stars with thermal radio emission, and the non-thermal sources surrounding stars, either continuum or maser sources. The majority of these latter are invisible in the optical and infrared. In a broader picture, stellar populations and star forming regions in the Milky Way and the Local Group are of particular interest since these allow studies of stellar evolution from the beginning to the end. The key scientific interests can be summarized as follows (Fig. 5.3):

- Radio activity as a probe of magnetism, that links the stellar surface to its interiors
- Mass accretion onto protostars and young stars
- Complexity of stellar mass loss
- Astrophysics of non-thermal continuum and line (maser) radiation, to probe stellar evolution
- 3D dynamics of group and stellar clusters
- Dynamical history of galaxies in the local universe

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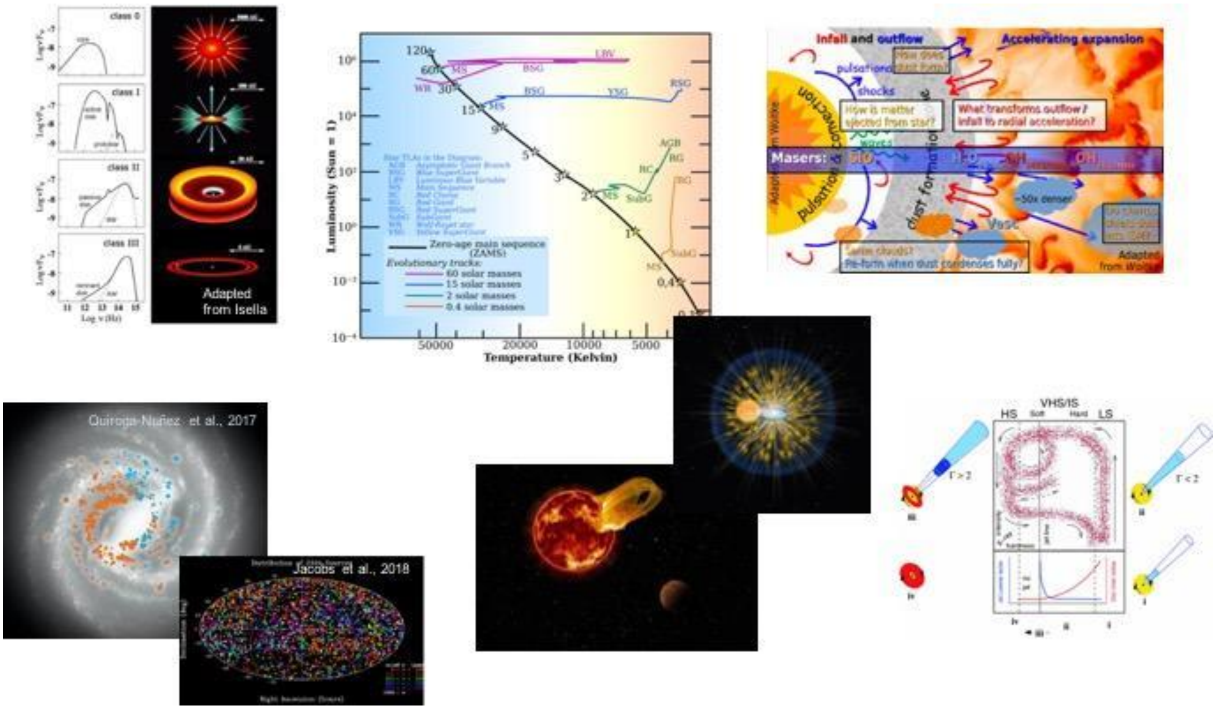


**Figure 5.3. Stars/Astrometry Key Science Themes.**

Fundamental to all there is ultimate astrometric accuracy: state-of-the-art calibration techniques -in-beam and multi-view techniques- and dramatic increase in astrometric samples. A key requirement is 1 microarcsecond astrometric precision dominated by thermal noise rather than systematics.

Possible key science projects discussed so far were:

- Trigonometry of stars using water methanol and masers: Milky Way, LMC ($\pi$=20 $\mu$as) and SMC ($\pi$=16 $\mu$as)
- Proper motion of ~20 stars in nearby galaxies using water masers, e.g. in M31 and M33 ($D$~800 kpc; $\mu$~30 $\mu$as/year)
- Surveying a large sample of stars (>>100) in unique sky areas with moderate astrometric accuracy (~10 $\mu$as)
  - Nearby star forming regions
  - Galactic Bulge and Center
  - Galactic spiral arms
  - Outer Galaxy

In addition, the group suggested adding these KSP topics:

- AGB stars: resolved imaging of stars and their maser clouds
- Test of General Relativity e.g. gravitational refraction by planets

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The above science cases can be addressed by flexible combinations of bandwidth, number of beams, number of subarrays, all within the current design capabilities of SKA1-Mid. This group, therefore, did not discuss the design implications in more detail. But they did consider commensal applications and minimal requirements for a SKA-VLBI array. The astrometric surveys with moderate accuracy (<2 GHz) have the best chances to be observed commensally, so it may be wise to prioritize these over the other projects. However, at least one of the highest precision astrometry programs should be pursued among the top priority KSPs.

**Figure 5.4. Women in action, from the stellar astrometry working group.**

Regarding the VLBI array requirements, the group (Fig. 5.4.) had the following recommendations:

- These KSPs require remote VLBI stations extending baselines beyond 6000 km with either *D* > 50m dishes equipped with phased-array feeds (PAF), or 4 x 25m arrays.
- The preferred uv-coverage requires intermediate-length (100-1000km) baselines (African VLBI Network, AVN)
- A truly ambitious implementation would be launching multiple spacecraft

According to our WP10 evaluation, the requirements for intermediate spacings is not new, this is common in all science themes. The need for phased-array feeds on large dishes or using clusters of ~25m class telescopes is motivated by the fact that astrometry of very faint targets requires both excellent baselines sensitivity and a large field of view, for simultaneous observation of target & calibrator(s). It is not clear whether these telescope(s)/arrays will be wide-spread available for global VLBI. There is talk about PAF-upgrade of some of the large EVN dishes. The only array of 25m-class telescopes in Europe, the Westerbork Synthesis Radio Telescope (also equipped with PAFs) will however be decommissioned by the end of 2021, according to plans. A globally distributed full SKA with single dishes would not satisfy these requirements, either. Unless of course, having arrays of SKA-dishes as “SKA stations” would be considered for the full SKA. This idea should be followed-up on by the community in further

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studies. Initial brainstorming has already started in the Netherlands, to possibly replace the old WSRT with a group of SKA dishes, but the idea is on hold as of mid-2021. One possibility to realize a next-generation Arecibo telescope would also be an array of small dishes on a rigid platform (Roshi et al. 2021, RD108).

As for the space-VLBI extension to the SKA, we understand the motivation: to achieve good baseline sensitivity to satellites with small dishes requires very sensitive counterparts on the ground. But this idea seems to be far-fetched for various reasons. For example, a space array that will compete with, or exceed the costs of the SKA, and strongly relies on SKA resources does not seem to be a realistic option at the moment.

## 5.3 Transients and Pulsars

There have been a lot of developments in the past few years that completely changed our view on transient science. While this is a field where extreme, never-observed-before astrophysical events will always be the highest priority at the time, it is hard to predict what will come next. But there are certain themes that will likely dominate the coming decade: studying gravitational-wave (GW) electromagnetic counterparts (EM), fast radio bursts (FRB), and finding/monitoring exoplanets. The latter idea surprised some of the discussion participants, but the idea here is to identify Jupiter-like exoplanets by their low-frequency outbursts; also, studying stellar flares, in general, is a key to investigating habitability zones around low-mass stars. As for the classical synchrotron transients, like black hole- or neutron star X-ray binaries, novae, supernovae, gamma ray bursts, tidal disruption events etc., they remain highly interesting. An additional notion that came up during the discussions is that magnetars, as a theme, should be given special attention. These are/may be connected to several of the above-mentioned phenomena, from GWs through FRBs to superluminous supernovae).

The unique combination of very high sensitivity and resolution, as well as excellent astrometric capability and calibration of a global SKA-VLBI array, is fundamental to achieving the science goals (Fig. 5.5., see also Annex 2). The practical goals are to monitor source size evolution to measure expansion velocity, determine proper motions for apparent projected jet speed, and derive parallax distances for events in the Milky Way/Local Group. Within the local universe of ~200 Mpc radius ("local" meaning that this range allows spectroscopic studies with middle-class telescopes, thus it is relatively easy to do) a relativistically expanding sources could reach resolution limits on a timescale of weeks, and a relativistic jet proper motion (~microarcsecond regime) could be detected on similar timescales with SKA-VLBI (as opposed to months with regular VLBI, cf. Paragi 2016, RD109). This, of course, assumes that certain events could get monitored with a high priority on short notice with the SKA, therefore this needs coordination with the SKA Transients science working group. In Table 5.3 we show

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typical timescales of transients, compiled for the “Locating Astrophysical Transient” workshop in 2013, the concluding event of the NEXPReS project[4].

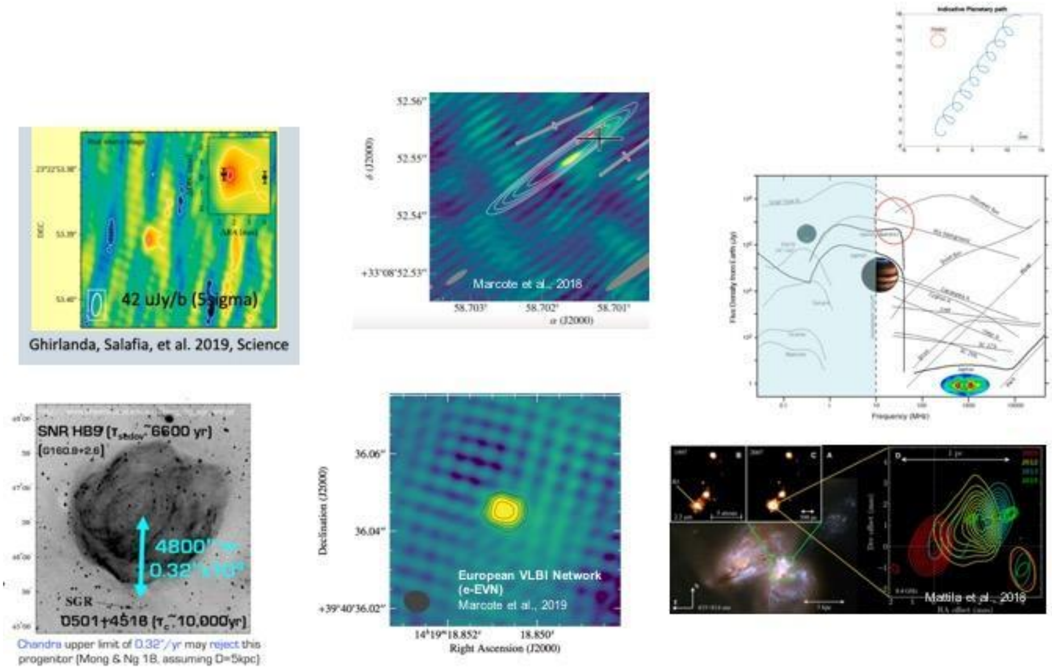


**Figure 5.5. Transient and Pulsars Key Science Themes.**

The group discussed possible observing strategies and operational issues for the two SKA1 telescopes separately, and came up with the following conclusions:

SKA1-Low:

- It is assumed that it will be 90% of the time idle, as conditions for EoR observations are expected to be fulfilled only about 10% of the time
- A lot of room for additional science, including VLBI but only a few telescopes are available at these frequencies
- Transient emission from exoplanets + astrometry could be the major science theme

[4] NEXPReS was an EC-supported program to promote real-time e-VLBI developments that boosted transient research with the (electronic-) European VLBI Network (EVN).

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**Table 5.3. Typical timescales for transient events**

| Transient | Early trigger | Typical duration |
|---|---|---|
| cataclysmic variables | | |
| RS CVn | hours | ∼1 day |
| classical and gamma-ray novae | within a week | months |
| "faint and fast" sub-class | 1 day | days-weeks (no known radio detection) |
| dwarf novae | hours | ∼1 day |
| "gap transients" | | |
| Ca-rich | days | 100 days (no known radio detection) |
| SN2002bj, PTF10bhp-like (.Ia) | hours | days (no known radio detection) |
| supernovae | | |
| Type Ia | days | years (no known radio detection) |
| Type Ib/c | days | months |
| Type II | days | years |
| gamma-ray bursts | | |
| short-GRB afterglows | hours to days | days |
| long-GRB afterglows | hours to days | weeks to years |
| prompt GRB emission | minutes | ? |
| X-ray transients | | |
| supergiant fast XRT | ? | no known radio detection |
| black hole X-ray binaries | hours–days | days–weeks |
| neutron star X-ray binaries | hours | days |
| isolated stellar-mass BH | ? | no known example |
| (super-)massive black holes | | |
| flaring AGN | ∼1 month | years |
| tidal disruption events | weeks | months–years |
| short radio transients ($t < 2$s) | | |
| Lorimer bursts prompt emission | real-time | 1–10 ms |
| Lorimer bursts afterglow | minutes | no known example |
| NS–NS mergers | minutes | no known example |

SKA1-Mid:

- ToO/triggering capability is really important
- Galactic transient parallax studies require
  - "VLBI every fortnight"
  - At least 8 VLBI beams for ultra-precise astrometry
- The e-EVN operational model (<<1/30$^{th}$ of a year!) could be considered: regular observations for robust operations, flexibility to transient and astrometry programs, efficiency of scheduling may be increased by filling e-days with background surveys and regular pointed observations
- All this requires strong LBA, EVN and EAVN support, as well as developing VLBI in Africa
- FAST is an opportunity rather than a competition – there is joint sky and frequency coverage with both SKA1-Low and SKA1-Mid
- FRBs and synchrotron transients, and in particular GW-EM counterparts will be major science themes, with both fields having a strong impact on cosmology as well, besides astrophysics

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The issue of an extended Australian (Low) / African (Mid) network came up. Regular use of SKA1-Mid outrigger antennas for transient science has also been considered for a long time, and adding them individually to VLBI observations (as discussed in the AGN group) would have several advantages for transients as well. The group also considered the requirements for SKA Regional Centres. At the time, most of these were just formulated as questions:

- Do we (user/correlator) need to rely on advanced data products from a SKA Science Regional Centre?
- Do we need SKA images from the VLBI subarray only or the full array?
- Can we get flux density (spectra) for N source (VLBI targets) in the field?
- Same for full Stokes information including polarization angle vs. frequency (therefore rotation measure)?
- Is it possible to get coordinates for new sources in the field to be sent to the VLBI centre prior to correlation (if not e-VLBI)?
- Can we get exact dispersion measures for fast transients, for coherent de-dispersion at the VLBI correlator (maybe expect this kind of data from a Science Regional Centre or the SDP?)

The actions were taken after the workshop to work towards (some of) the goals formulated during the meeting are described in the next section.

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# 6 Workshop outcomes for the SKA-VLBI science

The SKA-VLBI workshop discussions produced very interesting operational outcomes with respect to possible configurations and observing modes, alignment of the SKA-VLBI capability with the SKA1 design and its implementation, commensal opportunities with other SKA1 science, and simulations and data challenge exercises.

## 6.1 New SKA-VLBI configurations and observing modes

### 6.1.1 MultiView relative astrometric technique

As presented on the first day of the workshop, the MultiView technique with SKA-VLBI has the potential to improve the relative astrometric accuracy by an order of magnitude compared to what is achieved today, down to 1 µas for frequencies above 6 GHz, and allow precise astrometry for the lower frequencies. Figure 6.1 shows a comparison of the astrometric performance for the next generation instruments using different phase referencing techniques (from Rioja & Dodson 2020, RD026).

The MultiView method will use the multi-beam SKA1 capability to observe the target and different calibrators surrounding the target simultaneously, to correct for the astrometric errors introduced by the atmosphere. This technique can be applied to correct for the atmospheric effects caused by the ionosphere at lower frequencies and by the troposphere at the higher frequency regime.

Multiple beams were already included in the L1 requirements for the SKA1 telescopes. At the time, the request was formulated as “a minimum of 4 beams”, 1 for a target, and 3 for the calibrators. The SKA adopted the minimum requirement as an upper limit for the number of phased-array beams to be provided, even if the design allows for more. As has been demonstrated at the workshop, this bare minimum number of beams is not sufficient to achieve the highest astrometric precision. Especially for the lower frequency bands (below 2 GHz), it is necessary to increase the number of VLBI beams provided by the SKA telescopes from the nominal 4 to at least 6 or 8 VLBI beams to correct for non-planar ionospheric effects. Besides the astrometric precision, this would also allow for reaching the theoretical thermal noise level of the interferometer. For these reasons, an ECP was submitted to the SKA Project to change the design baseline description to accommodate an increase in the number of VLBI beams provided by the system (refer to Section 6.2 and Annex 3).

Table 6.1 shows the best possible systematic errors achieved using the MultiView method and the availability of in-beam calibrators with current and future capabilities (from Rioja & Dodson 2020, RD026). For SKA1-VLBI sufficient number of sources would be available for in-

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beam MultiView at 2 GHz and below, and for SKA2-VLBI at 6.7 GHz and below. For higher frequencies, the MultiView technique will require antenna movement to access further away calibrators.

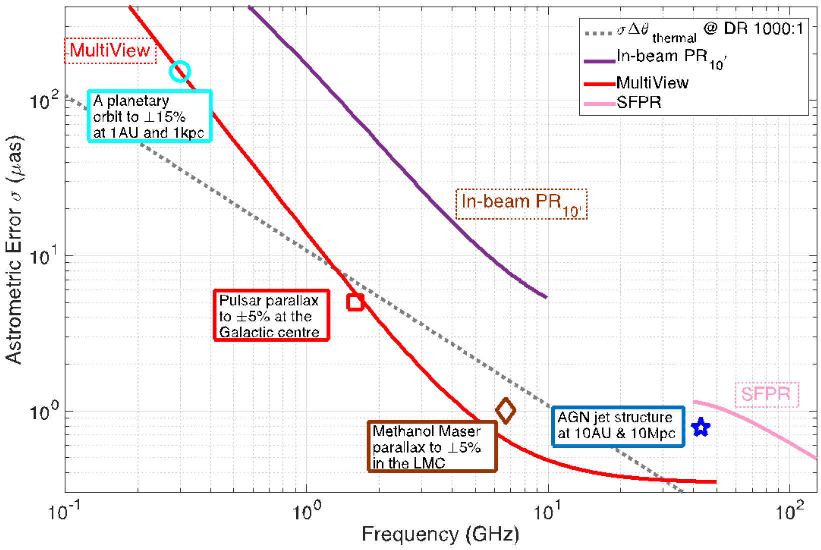


**Figure 6.1. Estimates of astrometric performance for next-generation instruments using the MultiView technique (with SKA1 and ngVLA, red) and the source frequency phase referencing technique (with ngVLA, pink), comparing with in-beam phase referencing results (purple). The thermal noise limit (grey dotted line) is calculated for the next generation instruments with a dynamic range DR 1000:1 and 6000 km baselines. Superimposed is shown the astrometric performance that could be achieved for different science cases (extracted from Rioja & Dodson 2020, RD026).**

**Table 6.1. MultiView method performance.** For different observing frequencies (column 1) the table lists the angular resolutions achieved in a 6000 km baseline (column 2) and the best possible systematic error for phase referencing using MultiView (column 3) and the required dynamic ranges (column 4). The table also includes a comparison between current capabilities (column 5) and SKA1-VLBI capabilities (column 7) and the number of in-beam calibrators available for each case (columns 6 and 8), and between parenthesis for SKA2-VLBI (from Rioja & Dodson 2020, RD026).

| Frequency $\nu$ (GHz) | Resolution $\theta_{\rm beam}$ (mas) | MV error $\sigma\Delta\theta^{MV}$ ($\mu$as) | Matching DR | $\Delta I_{\rm m}^{\rm current,1h}$ $\times 100$ (mJy/beam) | No. of in-beam sources | $\Delta I_{\rm m}^{\rm SKA,1h}$ $\times$ DR (mJy/beam) | No. of in-beam sources |
|---|---|---|---|---|---|---|---|
| 0.3 | 34 | 150 | 230 | 120 | $1.2^{\dagger}$ | 5.1 | $14^{\dagger}$ |
| 0.9 | 11 | 17 | 674 | 20 | 3.5 | 3.1 | 15 |
| 1.6 | 6.4 | 6 | >1000 | 4.9 | 2.9 | 2.1 | 5.5 |
| 5.0 | 2.1 | ~1 | >1000 | 2.3 | 0.4 | 2.4 | 0.4 (6) |
| 8.0 | 1.3 | ~1 | >1000 | 3.6 | 0.1 | 2.6 | 0.1 (2) |
| 15.0 | 0.7 | ~1 | 687 | 6.0 | 0.0 | 3.0 | 0.0 (0.4) |

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## 6.1.2 Individual SKA1 antennas and stations

During the SKA-VLBI workshop discussions, it was also argued that individual SKA1 antennas or stations should be made available for VLBI together with the beams from the phased-up core, in support of VLBI imaging and calibration. The additional antennas or stations will provide short uv-spacings to the VLBI images, in a similar way the e-MERLIN interferometer baselines are included in the EVN network. This inclusion will relax the requirements for simultaneous SKA Imaging that is necessary for all SKA-VLBI sciences cases. As a result, fewer SKA resources are used during VLBI observations, allowing for additional simultaneous and/or commensal observing opportunities, for example to use the same subset of SKA1-Mid antennas for transient follow-up and VLBI.

Operationally this observing mode will use several VLBI beams produced from a subarray formed by a phased-up core and different antennas or stations from the rest of the telescope array considered as separate subarrays, up to a maximum of 16 subarrays. This mode is possible as the SKA correlators are able to beamform using just one antenna or station, effectively providing the primary beam of that antenna or station, properly channelised in VDIF format. Additionally, only real-time calibration for beamforming will be required from the SKA Science Data Processor (SDP). It is anticipated that simultaneous SKA Imaging will not be required in this mode, but this needs to be confirmed by simulations.

For SKA1-Low there are no restrictions for this mode as the observing bandwidths are small and all the observing modes can be performed simultaneously for the full bandwidth for every subarray, with the only limitation being the number of subarrays available (a maximum of 16).

For SKA1-Mid the situation is different as the number of available processing resources (Frequency Slice Processors or FSPs) is limited (to a total of 26). Table 6.2 shows different scenarios, considering a different number of individual antennas (total number of subarrays) and the number of VLBI beams and observed bandwidth. The table shows the SKA correlator resources that are used for each case (FSPs), pointing out if there are resources left for additional commensal observing. One important characteristic of the CSP Mid design is that the same FSPs are capable of simultaneously processing the differently configured subarrays for the same observing mode. Therefore, increasing the number of subarrays in VLBI mode does not consume additional processing resources.

Table 6.2 also includes the aggregated data rates that would need to be recorded or sent in real-time to the VLBI correlator. Necessarily, the data rate increases with the number of beams, individual antennas and total observed bandwidth. Real-time data rates for e-VLBI observing are limited by the bandwidth of the available SKA external connection, currently planned for 100GE (i.e. 80 Gbps effective data rate). Values exceeding this limit have been shown in **bold**. These cases will necessarily be recorded during the observation and sent afterwards at more adequate data rates for the SKA external connection. The table also shows the number of FlexBuff or similar VDIF recorders (FB) needed for the different cases assuming

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a 32 Gbps recording capability per unit. Values are shown in blue when more recorders than initially planned are needed (>2).

**Table 6.2. Examples of configurations for the SKA-VLBI observing mode using a different number of beams and bandwidths from the phased-up core and a number of individual antennas (Keyword: FSP=Frequency Slice Processor, FB=FlexBuff VDIF recorder).**

| # subarrays | # VLBI beams | CSP MID resources | | | Aggregated data rate (Gbps) 2bit/2pol/Ny |
|---|---|---|---|---|---|
| | | VLBI+VLBI Vis. | SKA Img. | Commensal | |
| 1 (1 core) | 2 | 2 VLBI beams/5GHz (26 FSP) | | NO (26 FSP) | 78.1 (3 FB) |
| | 4 | 4 VLBI beams/500MHz (6 FSP) | 500MHz (3 FSP) | YES (9 FSP) | 15.6 (1 FB) |
| | | 4 VLBI beams/1000MHz (10 FSP) | 1000MHz (5 FSP) | YES (15 FSP) | 31.3 (1 FB) |
| | 8 | 8 VLBI beams/500MHz (15 FSP) | 500MHz (3 FSP) | YES (18 FSP) | 31.3 (1 FB) |
| | | 8 VLBI beams/1000MHz (20 FSP) | 1000MHz (5 FSP) | NO (25 FSP) | 62.5 (2 FB) |
| | 16 | 16 VLBI beams/500MHz (24 FSP) | | NO (24 FSP) | 62.5 (2 FB) |
| 2 (2 subcores) | 8=4x2 | 4 VLBI beams/500MHz per subarray (6 FSP) | 500MHz (3 FSP) | YES (9 FSP) | 46.9 (2 FB) |
| | 16=8x2 | 8 VLBI beams/500MHz per subarray (15 FSP) | 500MHz (3 FSP) | YES (18 FSP) | **93.8** (3 FB) |
| | 32=16x2 | 16 VLBI beams/200MHz per subarray (8 FSP) | 200MHz (1 FSP) | YES (9 FSP) | 50 (2 FB) |
| **16 (2 subcores + 14 SKA antennas)** | 22=4x2+14 | 4 VLBI beams/500MHz per subarray(6 FSP) +14SKA/500MHz | 500MHz (3 FSP) | YES (9 FSP) | **85.9** (3 FB) |
| | 30=8x2+14 | 8 VLBI beams/500MHz per subarray(12 FSP) +14SKA/500MHz | 500MHz (3 FSP) | YES (15 FSP) | **117.2** (4 FB) |
| | 46=16x2+14 | 16 VLBI beams/200MHz per subarray(8 FSP) +14 SKA/200MHz | 200MHz (1 FSP) | YES (9 FSP) | 71.9 (3 FB) |

**Bold**=no e-VLBI (external to SKA link), Blue= >2 FlexBuff VLBI recorders than initially planned

## 6.1.3 Additional SKA1-LOW stations at longer baselines

For SKA1-Low, a desire to have a few additional low-frequency stations distributed around Australia and nearby countries was discussed, following the International LOFAR Telescope (ILT) model, to add more elements to the VLBI networks at lower frequencies.

As a result, the SKA science director approached the engineering SKA groups to propose alternatives. As anticipated in this workshop (Section 4.5), the CSIRO Bluering project was presented at the 2019 SKA Shanghai meeting (Hampson et al. 2019, RD103), to develop a low-cost system for low-frequency VLBI in Australia, with new stations most probably located at the existing LBA observatories (Fig. 6.2) or near existing broadband network nodes.

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Other VLBI networks, such as the EAVN, are also supporting the expansion towards lower frequencies.

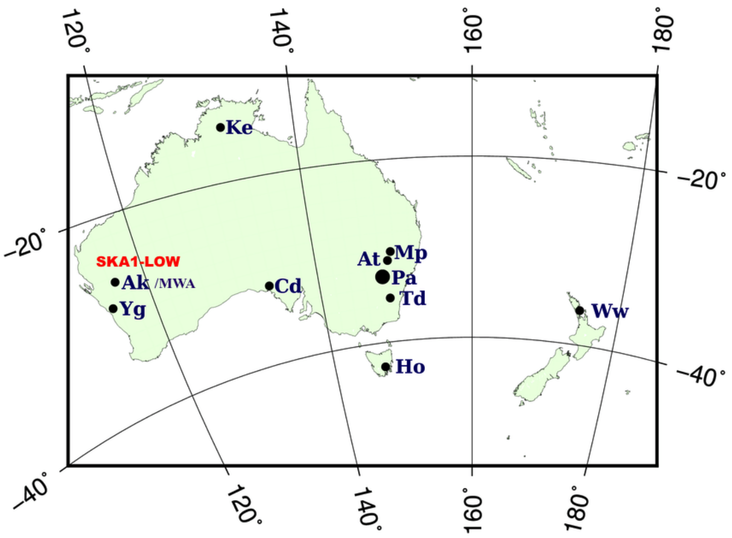


**Figure 6.2. The LBA network includes the AuScope geodetic network (Yg, Ke and Ho), with the location of the future SKA1-Low telescope collocated with ASKAP (Ak) and MWA observatories.**

## 6.2 SKA-VLBI capability alignment with SKA1 design

Throughout the workshop, the need to increase the number of VLBI beams available from the SKA1 telescopes was emphasised, to support the different SKA-VLBI science cases. The science discussions have shown the need to increase the number of beams to at least 8 for high precision relative astrometry but preferably to more sensitive VLBI beams to observe fields with a high density of targets. Another request was the ability to include a number of individual SKA dishes during VLBI observing, as explained in subsection 6.1.2. These dishes would provide the short spacings needed for observing primary flux and polarization calibrators.

Both needs materialised during the preparation of an Engineering Change Proposal (ECP) that was submitted to the SKA Office by the SKA-VLBI Scientist and endorsed by the VLBI science working group and JIVE Institute. The ECP focused only on the SKA1-Mid telescope to align the VLBI requirements with the telescope design. For SKA1-Low an equivalent request would incur additional costs, so a similar alignment may be considered later, during the SKA1 operational phase.

The ECP proposed to match the VLBI observing mode with the SKA1-Mid capabilities, using 16 VLBI beams per subarray configured for VLBI, and to configure a maximum of 16 subarrays for VLBI while limiting the number of total concurrent VLBI beams to no more than 46. The proposal was very respectful of SKA1 project plans and was kept as simple as possible,

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requesting a minimal modification to just one L1 system requirement to avoid impact on the Construction Schedule, Assembly, Integration and Verification (AIV) rollout plans, Capital Expenditure (CAPEX), Science and Commissioning plans, etc. The only element that would need to adapt their requirements is the Telescope Manager (TM) but there are no showstoppers from their architectural point of view and these capabilities will be already in place to support other observing modes. The telescope architecture or other elements designs are already compatible with the proposal, and interfaces will not need to be modified. The VLBI element, provided by an external SKA-VLBI Consortium, would need to be upgraded from the initially planned number of recording units (two) to at least four, to support the higher data rates, but interfaces with the SKA1 will not be modified as the VLBI design already allows for upgrades (RD007). The requirements for the Science Processing Centre that will host the VLBI equipment will need to be updated in terms of power consumption (from 4 kW to 6.3 kW in recording/transfer mode).

The SKA project approved the ECP in November 2020 and is currently in the implementation phase. Annex 3 reviews the SKA1 ECP process and includes the VLBI ECP form, outcomes and implementation plan.

## 6.3 SKA-VLBI capability implementation and science commissioning

Thanks to the alignment of the SKA-VLBI capability with the SKA1 design, VLBI with SKA1-Mid will provide 16 pencil VLBI beams from each phased-up core subarray. For broadband or multi-band observations up to 2 subarrays (core partitions) would be needed to be configured for each frequency band producing up to 16 VLBI beams each. Additionally, the remaining VLBI subarrays (for a maximum of 16 in total) can be formed by just one antenna in each, providing just one VLBI beam that will effectively be the primary beam of the Mid dishes and will be included as additional VLBI elements in the VLBI observation and correlation. In total 46 concurrent VLBI beams would be available for VLBI for the SKA1-Mid telescope.

Annex 4 presents a collection of *observing scenarios* to demonstrate the implementation of the VLBI capability for the SKA1-Mid telescope, starting from the simplest to the most complicated scenario. The scenarios for the SKA1-Low telescope are equivalent but without the need to define two subarrays to cover broad observing bandwidths, as its bandwidth is limited to 300 MHz.

As demonstrated by the observing scenarios there are different phasing strategies for VLBI with the SKA1 telescopes that would depend on each project in particular. But each type of project (targeted, survey or relative astrometry) could have a defined phasing strategy. The phasing solution would be the same when considering 4 VLBI beams or 16, but more computing load will be added, similar to the one required by other observing modes with 16 beams (e.g. pulsar timing PST).

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For science commissioning activities, it is recommended to start with the simplest solution and adopt boresight phasing for just one VLBI beam, defining just fast enough phasing latency to overcome variable and unpredictable weather conditions and keep the signal-to-noise ratio (SNR) on the beams above a reasonable value throughout the observation. For more than 2 VLBI beams off-boresight beamforming should be exercised, first adopting the isoplanatic assumption and later the pulsar timing off-boresight beamforming approach. Direction dependent effects may be considered later, with different alternatives that have been elaborated in the observing scenarios.

The proposed plan for SKA-VLBI science commissioning assumes that the different SKA1-Mid elements will be able to support more than 4 VLBI beams per subarray by the time of the Operations Readiness Review (ORR) milestone of the SKA project. The VLBI capability will be incorporated gradually, first just one beam for Bands 2/5 for Cycle 0 using boresight phasing, increasing to a maximum of 4 VLBI beams from one subarray in these same bands for Cycle 1, exercising off-boresight beamforming with isoplanatic or PST approach. For Cycle 2+ the four beams will be produced for Band 1 from one subarray, with direction-dependent effects considered. Once fully into the operational phase, the SKA1 Observatory will decide when to incorporate the rest of the VLBI beams and VLBI subarrays for Bands 1, 2 and 5.

## 6.4 Commensal Science Opportunities

The SKA1 telescopes design and operational model have been chosen to maximise scientific productivity by taking advantage of commensal observing opportunities, with different types of commensality considered (refer to Section 3 for details). In fact, even the most basic VLBI modes can be considered commensal since these make use of the SKA interferometer as well as phased-array beams.

The commensal observing requirements for SKA1 came in part from discussions with the transient science working group, with the support of VLBI experts (SKA Transient Science assessment workshop summary, 2014, RD110). This group established with the highest priority the commensal search on all data streams for real-time detection of fast radio transients. This capability increases by an order of magnitude the rate of transient detection and hence the scientific return.

For SKA-VLBI observations that target transient sources, having the ability to simultaneously characterise or search for pulsars and transients in the primary beam of the Mid dishes or the Low stations using Pulsar Timing (PST) and/or Pulsar -and transient- Search (PSS) beams can be key for the success of the project (Keane 2018, RD111). Another commensal opportunity would be to use a dedicated transient subarray made of one or few Mid antennas or Low

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stations observing simultaneously with the ongoing SKA1 projects to search, localise and follow-up transient events.

SKA-VLBI AGN science could also benefit from commensal observing. If resources are properly managed, the VLBI surveys could piggyback on the SKA1 surveys. As was brought up in the workshop, piggy-backing SKA1 surveys on the SKA-VLBI observations would make more sense, considering the stricter scheduling constraints for VLBI.

For stars and astrometry science with SKA-VLBI lots of observing time would be needed that could be efficiently handled using commensal observing. The degree of commensality would depend on the astrometric accuracy required. Astrometric surveys with moderate accuracy (<2 GHz) will allow other commensal projects, but the highest precision programs will not. However, the scientific importance of some of these high precision astrometry programs will sustain their consideration among the top priority KSPs.

Table 6.2 from Section 6.1.2 gives examples of possible VLBI observing configurations and points out when the processing resources allow for commensal science to be performed. From the perspective of SKA-VLBI science alone, the possibility of simultaneously obtaining other SKA1 products, on a wide range of angular scales, will allow revolutionary results.

## 6.5 SKA-VLBI simulations and SKA data challenges

The need for SKA-VLBI simulations and the benefit of performing SKA data challenges devoted to the VLBI capability was outlined during the workshop. The challenging data processing for the mm-wavelength observations of the black hole event horizon in M87 demonstrated the need for realistic synthetic observations produced from theoretical source models. One effort was the SYMBA pipeline (Roelofs et al. 2020, RD112). This pipeline generates raw synthetic data using the MeqSilhouette package (Blecher et al. 2017, RD113; Natarajan et al. 2020, RD114) that includes a tropospheric model and physically motivated antenna pointing offsets. The raw data is calibrated using the CASA VLBI calibration pipeline rPICARD (Janssen et al. 2019, RD115), applying a fringe fit and a priori amplitude calibration.

Similar efforts are underway to develop an end-to-end pipeline for cm-VLBI that would incorporate heterogeneous arrays, realistic sky models, tropospheric, ionospheric and calibration effects, subarraying options, instruments with multiple beams such as the SKA, etc. (Radcliffe et al. in preparation, RD116). Deane (2017, RD117) has shown the improvement in sensitivity that one beam from the phased-up MeerKAT would have on VLBI observations (Fig. 6.4 top), and Qwabe et al. (2019, RD118) explored the impact that removing one MeerKAT antenna would have on the overall MeerKAT imaging performance (Fig. 6.4 bottom). They found this to be negligible if imaging weights are properly adjusted. A more comprehensive study on different subarrays configurations will be needed to explore the survey speed versus

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the sensitivity parameter space for wide-field VLBI surveys (Radcliffe et al. in preparation, RD116).

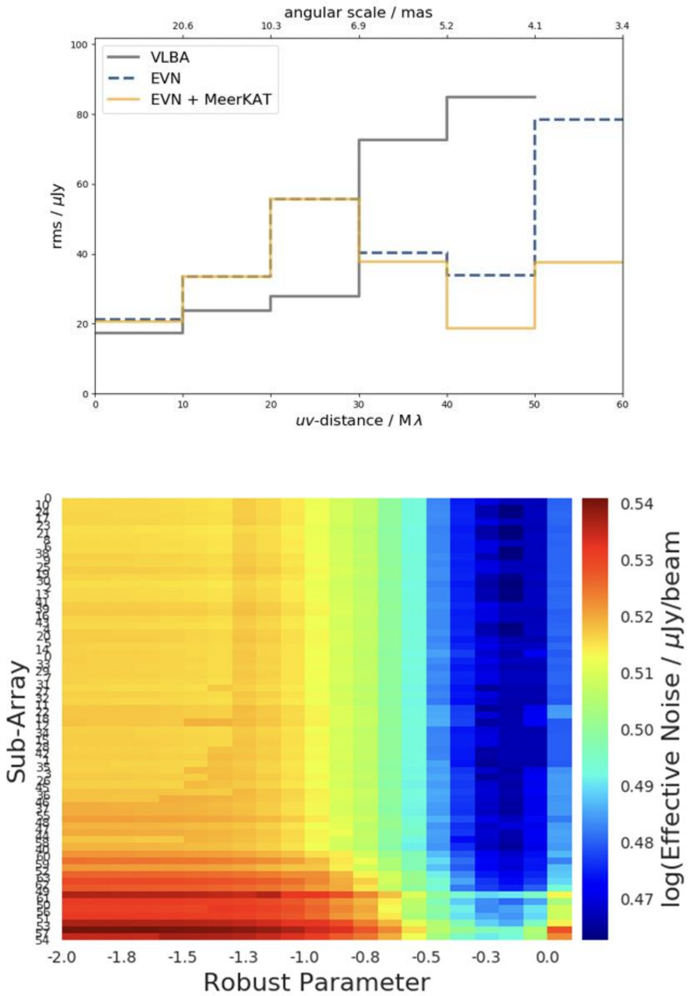


**Figure 6.4. Top: Demonstration of the enhancement of the EVN sensitivity by MeerKAT at 18 cm (Deane 2017, RD117). Bottom: MeerKAT effective noise versus robust parameter** when **removing a single antenna (left axis label) located at different distances from the array centre, (Qwabe et al. 2019, RD118)**

On the other hand, the SKA-VLBI data challenges could serve as a fantastic tool to train the community on the new VLBI capabilities with multi-beam instruments and test and stress the different VLBI pipelines. A working group has been formed led by Anna Bonaldi (SKAO) and Jack Radcliffe (SARAO, SKA-VLBI Science Working Group) to explore and prepare the different VLBI data challenges.

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# 7 SKA and VLBI historical perspective on current challenges

The SKA-VLBI workshop SOC had the honour to invite *Professor Richard T. Schilizzi* to wrap up the discussions and recommend future steps. Professor Schilizzi became the first SKA director in 2003 after a successful career in the field of radio astronomy for more than 40 years, including the establishment of JIVE in 1993 as the central data processing and support institute for the European VLBI Network.

The SKA culture and practices evolved from experiences in the VLBI world. Global mega-science facilities like the SKA are complex and expensive, with multiple players such as research and industrial organisations, governments and funding agencies. He specially mentioned the European Commission that plays a crucial role in supporting European VLBI.

A global science project that involves various countries faces many challenges. These intergovernmental projects need to cope with the countries' different funding cycles and investment histories, different scientific interests and levels of technology development, varied decision-making cultures and social cultures. A successful international scientific collaboration is driven by top-quality science, a mutual advantage for the individual parties, simple governance and management, good internal and external communication and the ability to please the community.

The VLBI community in Europe successfully pioneered the establishment and operation of large-scale distributed infrastructures that depend on the collaboration of many partners, with limited resources but adhering to a common vision. Today there are examples of many successful VLBI networks and collaborations.

Until the full realisation of the SKA, the VLBI arrays around the world will continue to be the premier facilities for high angular resolution astronomy, and in particular the SKA-VLBI capability will offer a unique sensitivity/resolution parameter space. The JUMPING JIVE project WP10 "VLBI with the SKA" has covered the areas that required attention to include the VLBI capability in the SKA1 telescopes: science priority, design and implementation, operations and governance.

The SKA-VLBI workshop presented the excellent VLBI science that can be realised with the SKA1 and the fundamental questions that can only be answered with VLBI. The strategy to embed VLBI in the current SKA Key Science Projects is the way to go. Therefore, it was suggested to raise the visibility of the VLBI science with the SKA1 at national and international

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SKA meetings[5] and elaborate SKA-VLBI science data challenges and simulations supported by the SKA VLBI science working group.

Following steps for the area of design and implementation would be to establish a VLBI technical team to interface with SKAO engineers to support the implementation of the VLBI capability during the SKA1 construction phase, turning assumptions into reality[6].

The VLBI capability for SKA1 requires coordination with the VLBI networks and other observatories and a proposed SKA-VLBI Consortium (RD015) would facilitate this collaboration. It was also suggested to establish a VLBI operations team to interface with the SKA Observatory. At the management level, the Global VLBI Alliance with SKA participation would be the perfect forum for high-level policies.

[5] JUMPING JIVE project has supported this effort for EWASS 2018, EVN Symposium 2018, SKA Spain days 2019, SKA Portugal meeting 2019, SKA General Science meeting 2019, EAS 2020, CASA-VLBI workshop 2020, SKA General Science meeting 2021, SKA public talk 2021 and AERAP Africa-Europe Summit 2021.

[6] JUMPING JIVE project is already supporting SKAO in the assessment of post System CDR ECPs in areas related with the VLBI capability.

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# 8 Conclusions

The VLBI capability for the SKA1 telescopes is revealing as a fundamental piece in the intricate jigsaw puzzle to build this challenging scientific facility. Not only the success of several of the SKA1 high priority science objectives relies on the high angular resolutions only provided by VLBI, but the way forward towards the completion of a full-scale SKA will nurture on the 50 years of experience performing VLBI observations.

Many of the scientists that are now supporting the SKA project come from the VLBI world. Some of them joined us in the workshop but we also welcomed scientists from the new generations, trained on large astronomical surveys and big data problems. Together we discussed the most relevant key science themes in the field of precision astrometry, large field-of-view VLBI, VLBI surveys and transient science. These key science themes will guide the elaboration of the concrete observing projects, the Key Science Projects only achievable by means of the SKA-VLBI capability.

The recently published EVN Vision document (JUMPING JIVE WP7 effort, RD119) establishes the key role of the European VLBI Network and VLBI in the future astronomy landscape. VLBI with SKA will add very distinctive features that will enhance the scientific return:

- access to southern skies,
- high sensitivity on VLBI scales angular resolutions,
- multiple sensitive beams for surveys and ultra-precise astrometric applications,
- better quality calibration products,
- RFI controlled environments and receivers,
- inclusion of individual SKA antennas in the VLBI networks in support of VLBI imaging and calibration,
- flexible and commensal observing to efficiently collate VLBI programs with SKA1 surveys, obtain complementary SKA1 products at different angular scales and monitor high priority transient targets on short notice.

The key science themes discussed all take advantage of the special characteristics of the SKA-VLBI capability. However, the success of the VLBI projects including the SKA will strongly depend on the VLBI network uv-coverage, the dynamic range and ultimately, on the image fidelity, as will be demonstrated by the proposed simulations. Intermediate baselines in Africa and Australia and the development of the networks towards the lower observing frequencies will be necessary.

The impact of the JUMPING JIVE project WP10 was tangible throughout the workshop. During the first stages of the WP10 effort, the liaison with the engineers and scientists that were developing the VLBI capability for the SKA1 telescopes was fundamental to guide the successful design and definition of the requirements and interfaces. The knowledge about the VLBI capability and its full potential was transferred to the VLBI science working group that

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helped in the elaboration of the Portfolio of SKA-VLBI science cases, a collection of examples on how to better exploit the capability. This deep knowledge was demonstrated in the variety of science that was presented during this workshop and guided the parallel KSPs discussions.

The work of the JUMPING JIVE WP10 culminated in the preparation and presentation of an Engineering Change Proposal for the alignment of the VLBI requirements with the actual design of the VLBI capability. The successful approval of this ECP by the SKA Project in November 2020 allows the realisation of most science cases.

The imminent start of the construction of the SKA1 telescopes leads to a bright future for SKA-VLBI science.

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# ANNEXES

## ANNEX 1: Workshop Participant List

**Table 1. Workshop participant list**

| # | Last Name | First Name | Affiliation | Talk |
|---|---|---|---|---|
| 1 | Akahori | Takuya | National Astronomical Observatory of Japan | |
| 2 | An | Tao | Shanghai Astronomical Observatory | Talk |
| 3 | Anton | Sonia | CIDMA & Dep Physics - Univ Aveiro | |
| 4 | Argo | Megan | University of Central Lancashire | |
| 5 | Asabere | Bernard Duah | ASTRON | |
| 6 | Atri | Pikky | ICRAR-Curtin University | INVITED |
| 7 | Beswick | Rob | University of Manchester | |
| 8 | Bonaldi | Anna | SKAO | Talk |
| 9 | Braun | Robert | SKAO | Talk |
| 10 | Browne | Ian | JBCA | |
| 11 | Caleb | Manisha | Jodrell Bank Centre for Astrophysics | INVITED |
| 12 | Charlot | Patrick | Laboratoire d'Astrophysique de Bordeaux | |
| 13 | Chen | Hongying | JBCA | |
| 14 | Chibueze | James | North West University | INVITED |
| 15 | Choi | Yoon Kyung | MPIfR | INVITED |
| 16 | Chrysostomou | Antonio | SKAO | Talk |
| 17 | Colomer | Francisco | Joint Institute for VLBI ERIC (JIVE) | Talk |
| 18 | Cullen | Jimmy | The University of Manchester | |
| 19 | Diamond | Phillip | SKAO | Talk |
| 20 | Diamond | Joseph | SKAO | |
| 21 | Dodson | Richard | ICRAR/UWA | Talk |
| 22 | Etoka | Sandra | JBCA - Manchester University - UK | Talk |
| 23 | Evans | Rhodri | University of Namibia | Talk |

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| # | Last Name | First Name | Affiliation | Talk |
|---|---|---|---|---|
| 24 | Forbrich | Jan | University of Hertfordshire | INVITED |
| 25 | Garcia Miro | Cristina | SKAO | Talk |
| 26 | Garrett | Michael | University of Manchester & Leiden | |
| 27 | Giroletti | Marcello | INAF Istituto di Radioastronomia | INVITED |
| 28 | Habeeb | Nusrin | United Arab Emirates University,UAE | |
| 29 | Hodgson | Jeffrey | Korea Astronomy and Space Science Institute | |
| 30 | Imai | Hiroshi | Kagoshima University | |
| 31 | Jones | Sandy | Geoscience Australia | |
| 32 | Kadler | Matthias | Uni Wuerzburg | |
| 33 | Kay | Hilary | University of Manchester | |
| 34 | Keane | Evan | Square Kilometre Array Organisation | Talk |
| 35 | Kharb | Preeti | National Centre for Radio Astrophysics - Tata Institute of Fundamental Research | Talk |
| 36 | Kirsten | Franz | Chalmers University of Technology | Talk |
| 37 | Kobayashi | Hideyuki | National Astronomical Observatory of Japan | Talk (on behalf of Hirota Tomoya) |
| 38 | Laing | Robert | Square Kilometre Array Organisation | |
| 39 | Li | Jingjing | Purple Mountain Observatory, Chinese Academy Sciences | |
| 40 | Lindqvist | Michael | Onsala Space Observatory | |
| 41 | Lopez | Ericson | Quito Astronomical Observatory of Ecuador | |
| 42 | Marcote | Benito | Joint Institute for VLBI ERIC (JIVE) | Talk |
| 43 | McKean | John | ASTRON / Kapteyn Astronomical Institute | INVITED |
| 44 | Mohan | Prashanth | Shanghai Astronomical Observatory | |
| 44 | Morabito | Leah | Durham University | INVITED |
| 45 | Motta | Sara Elisa | University of Oxford | |

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| # | Last Name | First Name | Affiliation | Talk |
|---|---|---|---|---|
| 46 | Muxlow | Tom | Jodrell Bank Centre for Astrophysics, University of Manchester | |
| 47 | Nair | Dhanya G. | Joint Institute for VLBI ERIC (JIVE) | |
| 48 | Njeri | Ann | Jodrell Bank Centre for Astrophysics | |
| 49 | Paragi | Zsolt | Joint Institute for VLBI ERIC (JIVE) | Talk |
| 50 | Perez Torres | Miguel | Instituto de Astrofisica de Andalucia (IAA-CSIC) | Talk |
| 51 | Phillips | Chris | CSIRO | Talk |
| 52 | Porcas | Richard | Max-Planck-Institut fuer Radioastronomie, Bonn | |
| 53 | Qwabe | Nkululeko | South African Radio Astronomy Observatory (SARAO) | |
| 54 | Radcliffe | Jack | University of Pretoria / SARAO | INVITED |
| 55 | Reynolds | Cormac | CSIRO Astronomy and Space Science | Talk |
| 56 | Richards | Anita | JBCA, University of Manchester | Talk |
| 57 | Rioja | Maria | ICRAR-UWA;CSIRO;OAN | |
| 58 | Sargent | Mark | U. of Sussex, Astronomy Centre | Talk |
| 59 | Schilizzi | Richard | The University of Manchester | INVITED |
| 60 | Simard | Dana | University of Toronto | INVITED |
| 61 | Sohn | Bong Won | Korea Astronomy and Space Science Institute | |
| 62 | Umana | Grazia | INAF-OACT | |
| 63 | van Langevelde | Huib | JIVE | Talk |
| 64 | Venturi | Tiziana Venturi | INAF, Istituto di Radioastronomia | |
| 65 | Wilkinson | Peter | University of Manchester | |
| 66 | Williams | David | University of Oxford | Talk |
| 67 | Wrigley | Nick | Jodrell Bank Observatory | |
| 68 | Xu | Ye | Purple Mountain Observatory, Chinese Academy Sciences | |

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# ANNEX 2: SKA-VLBI Key Science Projects paper

PROCEEDINGS OF SCIENCE

## SKA-VLBI Key Science Programmes

**Zsolt Paragi**[*][†]
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*Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands*
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**Antonio Chrysostomou, Cristina García-Miró**
*Square Kilometre Array Organisation (SKA), Jodrell Bank Observatory,*
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A significant fraction of the observing time with the two phase-I SKA components (SKA1-LOW SKA1-MID) will be spent on Key Science Projects led by member country scientists. The various SKA Science Working Groups, including the VLBI Focus Group are in the process of defining KSPs that are aligned with the High Priority Science Objectives of the SKA. At the moment it is not clear how the special observing mode of SKA-VLBI - when the SKA1 components are phased-up and included in VLBI networks - could be incorporated in KSPs. Our VLBI community needs to be prepared by the time the KSP proposal calls are expected (mid-2020s). We outline the basic concept of SKA-VLBI, and some possibilities for us to engage in SKA KSPs.

*14th European VLBI Network Symposium Users Meeting (EVN 2018)*
*8-11 October 2018*
*Granada, Spain*

[*]Speaker.
[†]The “VLBI with the SKA” work package is part of the Jumping JIVE project, that has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730884.


http://pos.sissa.it/

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

## 1. VLBI with the SKA

The Square Kilometre Array (SKA) is a next generation radio facility that will eventually have a collecting area of about a square kilometre, and baselines up to thousands of kilometres[1]. The science case of this ultimate very long baseline interferometer (VLBI) array was initially published at the end of the 1990s [1], and the first comprehensive science case was compiled in 2004 [2]. The challenge of building a fast survey machine that images large portion of the sky in a relatively short time, but at very high resolution, was realised from the very beginning. The "Carilli & Rawlings" book in 2004 highlighted five possible key science projects. These were "The cradle of life", "Strong-field tests of gravity using pulsars and black holes", "The origin and evolution of cosmic magnetism", "Galaxy evolution, cosmology and dark energy", and "Probing the dark ages". With time it became clear that the various envisaged imaging (EOR, continuum, HI etc.) and time domain (pulsar search, pulsar timing) surveys require most of the collective area in very short spacings, and this has driven the design of the instrument ever since. There will be two components of phase I SKA with different frequency coverage. SKA1-LOW (50 MHz – 350 MHz) will be in Australia, with maximum baseline length of about 65 km. SKA1-MID (0.35 GHz – 15.3(24.0) GHz) will be built in South Africa, with maximum baseline length of about 150 km. The second phase of the SKA will provide the full sensitivity, and a resolution that is 20x that of the phase I components. The latest collection of science cases were published in 2015 by the SKA Organization (SKAO), with headquarters in Jodrell Bank, UK [3].

The SKAO is in continuous discussion with the community about how to best address its science goals. There are a number of Science Working Groups and Focus Groups working on this. A main concern for the VLBI community is how to carry out very high angular resolution science during phase I of the project. In 2015 the VLBI working group was formally established, with co-chairs Cormac Reynolds (CSIRO) and Zsolt Paragi (JIVE)– the latter replaced in 2018 by An Tao (ShAO). The idea of having the core of the SKA phase I components phased-up, just like the Westerbork Synthesis Radio Telescope was in the EVN until quite recently, came naturally. A single tied-array beam will be significantly smaller than an arcsecond, but it will be possible to form several independent beams in the same sub-array, looking at different targets/calibrators within the primary field of view of the SKA dishes [4, 5]. The VLBI working group helped to define L0 science requirements, and L1 technical requirements together with the various SKA Consortia, and established a few initial use cases. One of the important requirements was for simultaneous VLBI (phased-array) and SKA1 interferometer data products. The advantages are straightforward for calibration: in VLBI there are no primary flux density calibrators, because compact sources are variable. For science: we will have for the first time simultaneous information on a wide range of angular scales, clearly beneficial to understand our targets together with their environments, from arcminutes to (sub-)milliarcsecond scales. This is demonstrated in Fig. 1. Another noteworthy requirement is real-time VLBI data streaming capability from the SKA1 components : the e-EVN is an SKA pathfinder not just as an instrument, but it can also be considered as a pathfinder for SKA-VLBI operations.

[1] http://www.skatelescope.org



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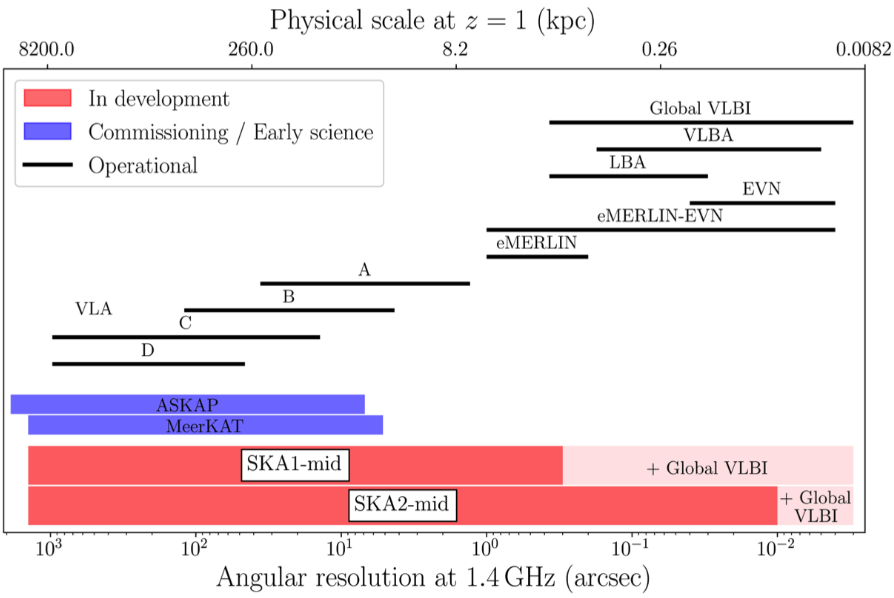


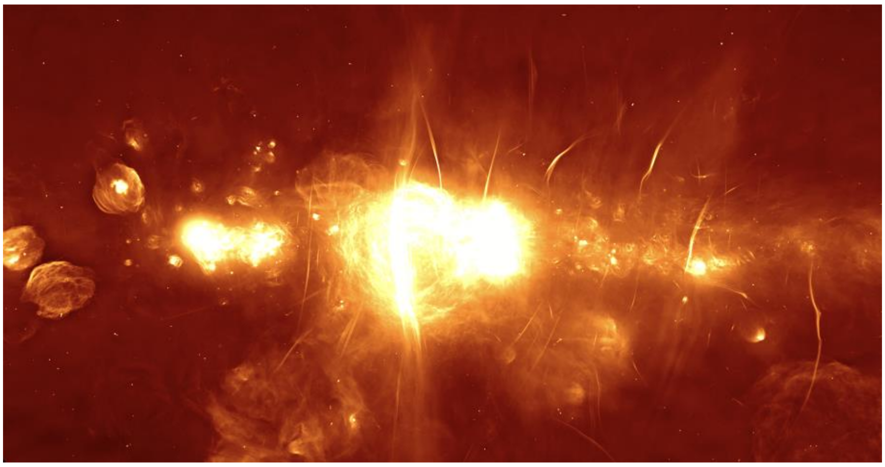

Figure 1: Above: angular scales (and corresponding spatial scales at $z = 1$) probed by various current and future interferometers working in the cm wavebands. Courtesy of Jack Radcliffe. Below: the Galactic Centre – the first public image from the 64-element SKA1-MID precursor MeerKAT. From: *https://www.ska.ac.za*



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## 2. EVN and SKA-VLBI science priorities

There were a number of high profile VLBI results that motivated us to push for VLBI capabilities in the SKA [4]. For example the accurate distance determination of the dwarf nova SS Cyg – requiring astrometric VLBI observations triggered within a day – that resolved a debate about accretion disc theory [11], the direct evidence for jet-driven, large-scale neutral and molecular outflow in the recurrent young radio source 4C12.50 [12], and the identification of shocks where very high energy emission originate in the classical Nova Monoceros 2012 [13]. Large field-of-view VLBI surveys [14], comparing global VLBI astrometry results with future Gaia catalogs, and observing tidal disruption events (TDE) were in the wish list for ultra-sensitive SKA-VLBI observations as well [4]. It is still somewhat a surprise just how much our field has developed in the past three years. We have detected and localised a repeating fast radio burst (FRB) on milliarcsecond scales, which opened a whole new chapter in the VLBI study of short transients (see Fig. 2, and references). We can measure the jet collimation profile in an active galactic nucleus (AGN) from $10^2$ to $10^4$ gravitational radii from the supermassive black hole, using space-Earth baselines to RadioAstron [15]. We detect dozens of targets – also aided by primary beam correction within the EVN – in deep fields [16], we find evidence for kpc-scale optical jets by comparing VLBI and Gaia astrometry [17], and we resolved ejecta from a TDE in Arp 299B [18]. Perhaps most unexpected, we resolved ejecta of the first-ever electromagnetic counterpart to a gravitational wave event GW1701817 [19, 20] – all of these results have been presented at this symposium. Clearly, there is a lot of momentum to push for major VLBI observing programmes on these (and other) topics, that include the SKA.

The range of topics largely overlaps with the science the EVN pursues in the coming decade [21]. We have to identify those areas where the SKA1 components will have a unique contribution to VLBI. For example: surprising as it may sound, the quality of amplitude calibration of an interferometer has an effect on its resolution power in the high signal-to-noise ratio regime ($\sim$S/N>100; [22]). Station calibration at the level of $\sim 1\%$ will be needed to accurately measure source sizes (under some assumptions) smaller than about 1/10th of the beam size. While at low S/N knowing the total flux density is critical (cf. [20]) – SKA1 data on targets and calibrators will help in both cases. Similarly, SKA1 will provide very precise polarization characterisation of our targets and calibrators on arcsec scales, which will help to accurately calibrate the cross-hand VLBI data products, to measure the frequency dependent fractional linear and circular polarizations, the polarization angles as well as the rotation measure in source components seen on VLBI scales. The multi-beam capability of SKA1-MID means that it may be possible to use a number of in-beam calibrators for ultra-precise (down to a few microarcseconds) relative astrometry, on sub-mJy targets. This has important implications for stellar (continuum and maser), pulsar, and transient astrometry observations. There is a lot of synergy in VLBI studies of various SKA1 surveys fields or particular targets of interest, let it be continuum, spectral line, or time-domain, even if the SKA1 components are not always part of the follow-up VLBI observations. The demand on VLBI observations will likely increase to an extent that requires an extension to current observing sessions, possibly also allowing for more regular “EVN-lite" observations with a subset of telescopes, to follow-up SKA1 triggers (an idea that has been around in the EVN for a while).



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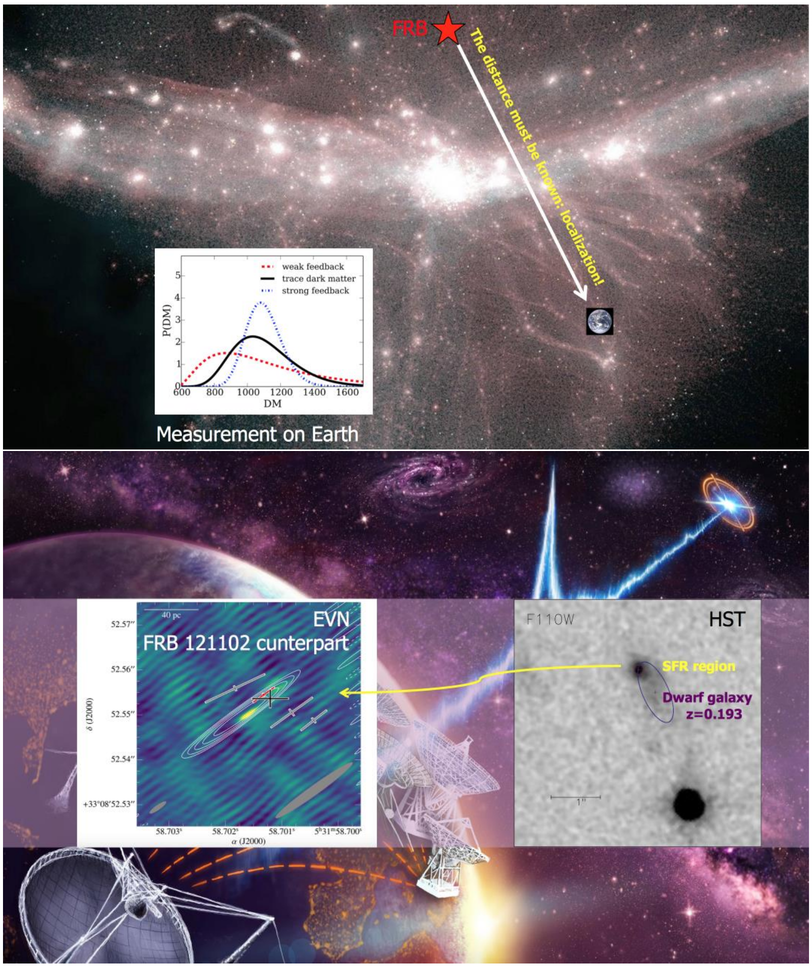


Figure 2: Above: one of the highest priority science objectives of the SKA. The milliseconds-duration signals from fast radio bursts (FRBs) get dispersed in the intergalactic medium. The distribution of the measured dispersion measures (DM; inset from [6]) for several hundreds of FRBs – in a given redshift bin – sheds light on the distribution of baryonic matter in the Universe. This requires sub-arcsec localization at high redshifts. Background image: *https://www.alanrduffy.com*. Below: JVLA and EVN localization of the repeating FRB121102. The short pulses detected by the EVN are co-located within ~10 mas of a compact, persistent radio source wihtin a star forming region in a dwarf galaxy at $z = 0.1927$. Ultimate evidence that FRB-like signals (may) have cosmological origin [7, 8, 9, 10]. Artist's impression: Danielle Futselaar.



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### 3. SKA Key Science Programmes: strategies for VLBI

The SKAO and the science working groups have compiled a list of forty high priority science objectives from eight broad topics, and a subset of thirteen "highest-ranked HPSOs". These range from studies of the epoch of reionization with SKA1-LOW, test of GR with pulsars (MID), observing atomic Hydrogen nearby and at high redshifts (MID/LOW), FRB cosmology (MID/LOW), “Cradle of Life” (planet and star-formation, structure of the Milky Way using SKA1-MID), the origin of magnetic fields (MID/LOW), and continuum surveys for cosmology as well as for the study of star formation history in the Universe (MID). Several of these will heavily rely on additional VLBI observations. There have been initial SKA-VLBI “use cases” established for pulsar astrometry, stellar deep fields, Galactic Structure (two independent maser use cases), synchrotron transient follow-up, and AGN surveys. These use cases aim to define the observations and the required SKA resources for a given science goal. More of these ideas will have to be worked out in more detail, as the SKA1 design stabilises through 2018/2019.

The KSPs for the SKA have not been defined yet, but these will be large projects “that require large observing time allocations over a period longer than one Time allocation cycle” (SKA KSP Framework Paper). It is expected that a typical KSP will ask for 1000h of observations over 3–4 years. This is about the same as having for example all ten 24h e-EVN sessions per year dedicated fully to a single SKA-VLBI KSP for four years. Having matched resources might be a challenge, but may not be that critical considering the global VLBI resources available world-wide. The bottle neck might actually be the time available for VLBI at the SKA1 components. Therefore it is not only the science cases, but their possible realisation will have to be thought through carefully. One way of getting around this problem is to incorporate a SKA-VLBI element (requiring $\ll 1000\,\mathrm{h}$ in itself) in regular SKA KSPs. Another possibility would be doing piggy-back VLBI observations on various SKA1 surveys, although this may require some special VLBI scheduling requirements taken into account when organizing the survey observations. We will have to understand the limitation of commensal operations within the SKA very well. This is important also because we will preferentially need the SKA1 data products in all regular SKA-VLBI observations. Another consideration is to request some of the SKA1 dishes – those that are usually not used in SKA surveys requiring dishes in the core of the array only – being available for VLBI for extended periods of time (for sufficiently bright targets).

These ideas will be discussed in specific SKA and SKA-VLBI Key Science Projects workshops, starting already in 2019. While the final construction of the SKA1 components is in the future, it is worth noting that MeerKAT is already operational, and the first dish of the future African VLBI Network (the Ghana telescope) has already produced VLBI fringes. We may also expect the SKAO will allow for shared-risk science verification observations during commissioning. It is time we get ready for SKA-VLBI!

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# ANNEX 3: SKA1 Engineering Change Proposal for VLBI

The SKA1 baseline at a given time is a description of the different aspects of the project with respect to technical, cost, schedule and contracts details. Technical changes to the SKA1 baseline are allowed during the project and are handled in two ways:

1. Permanent Scope changes are made with the proposal, assessment, review and implementation of an Engineering Change Proposal (ECP).
2. Temporary changes are made with the request, assessment, review and implementation of Concessions. Concessions are used when an item/service presents an inability to meet one of its functional performance or technical requirements and allow delivery of non-conforming items/services. Concessions are issued as either Deviation or Waiver Permits.

## ANNEX 3.1: SKA1 Engineering Change Proposal Process

The permanent change request process is a closed-loop process where the objective of the change is to update the current baseline (Fig A.1). The process is divided into the following 4 steps.

**Step 1.0:**

Change requests are completed by anyone in the SKA Organisation. For external requests, they are routed via the respective Product Managers (PM) who will complete the change request.

The change request is initiated by copying and completing an ECP Form. A Jira ticket is raised in the TRKECP project to track the work progress of the ECP. The completed change request is vetted by the SKAO Configuration Management department and registered on the eB database.

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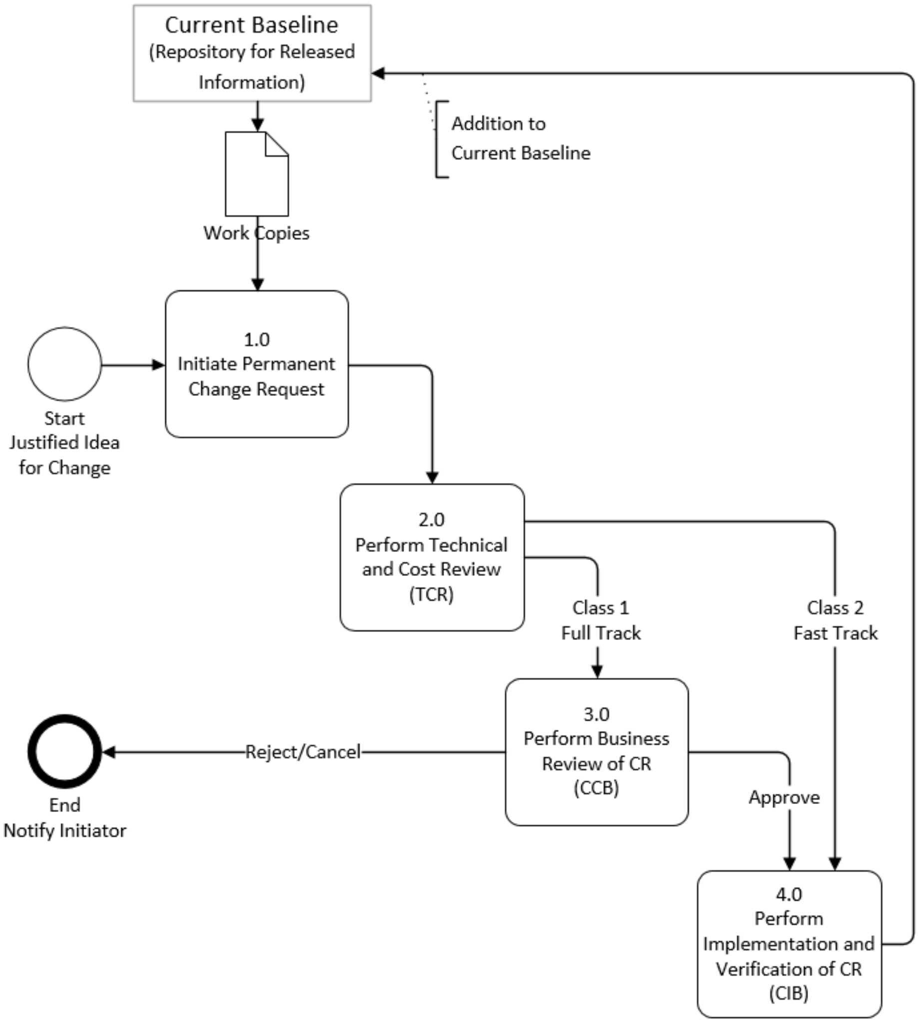


**Figure A.1. SKA1 project Engineering Change Proposal process**

**Step 2.0:**

The change request is assessed for Technical and Cost impact.

- Class 2 (Major) changes are assessed for Technical, Cost and Schedule impact by the Telescope Delivery Team (TDT), acting as the SKA Technical and Cost Review (TCR) Panel. These changes can be expedited by the TDT.
- Class 1 (Critical, including modifications to System requirements) changes are assessed for Technical, Cost and Schedule impact by the TDT, acting as the SKA TCR Panel. These changes are recommended for disposition to the Configuration Control Board (CCB).

Cost and Schedule inputs are provided by the Programme Management Office (PMO).

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Technical assessment is done by the TDT with inputs from respective Product PM's and the Dish Consortium (where required) and the Meerkat + team (where required).

The SKA configuration manager (CM) participates in the TCR meetings in order to capture impacts in eB.

Class 2 changes are dispositioned by the TCR Panel. Class 1 changes are referred to the CCB with recommendations on the course of action from the TCR Panel.

**Step 3.0:**

Class 1 (Critical) changes are assessed and dispositioned by the Programme Board (PB), action as the SKA CCB. The CCB assesses the change from a business perspective and reviews the inputs from the TCR Panel. The CCB dispositions the change.

The CCB core members are:

- SKA1 Programme Director (Chair)
- SKA1 Director of Science
- SKA1 Director of Operations
- SKA1 Head of Mission Assurance (Deputy Chair)

It is intended that decisions will be unanimous. If agreement cannot be reached it will be escalated by the chair to the Director-General.

The Programme Director in his role in the CCB is supported by:

- SKA1 Head of Project Management Group (further supported by relevant PMs)
- SKA1 Project Engineer (further supported by relevant telescope and system engineers)
- SKA1 Head of Computing and Software (further supported by relevant software engineers)
- SKA1 System Scientist
- SKA1 Host Country Execution Managers

The SKA CM participates in the CCB meetings in order to capture impacts and decisions in eB.

**Step 4.0:**

Implementation of approved changes are executed and verified by the TDT, acting and the Configuration Implementation Board for SKA. ECP implementation reports may be required from affected Providers and the respective PMs are tasked to verify implementation. Implementation of Technical changes is recorded under Configuration Management (eB).

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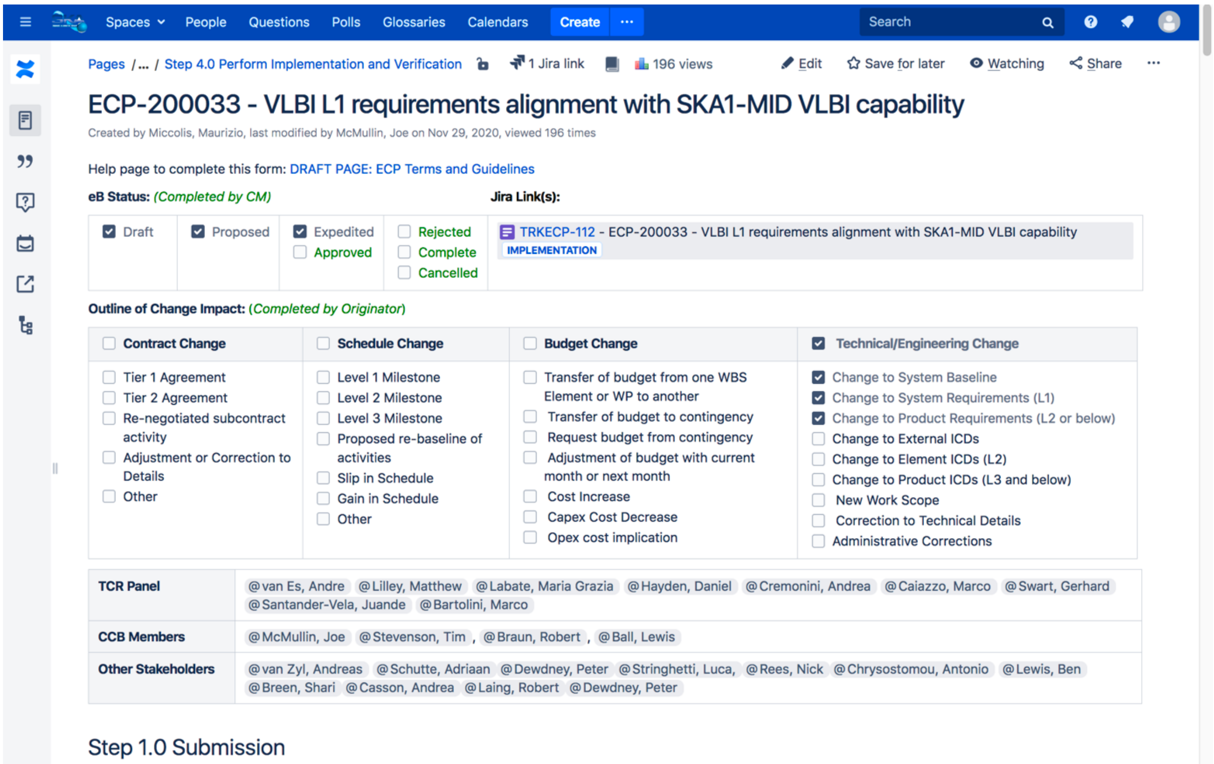
# ANNEX 3.2: Engineering Change Proposal for VLBI

An Engineering Change Proposal (ECP-200033) was prepared and submitted to the SKA Office in July 2020 by the JUMPING JIVE SKA-VLBI scientist endorsed by the VLBI science working group and the JIVE Institute. This effort was sponsored by Maurizio Miccolis, SKA Observatory software project manager. The ECP was initially approved by the SKA Technical and Cost Review (TCR) panel, but the Configuration Control Board (CCB) decided to put it on hold until after the SKA Construction Proposal submission in September 2020. The VLBI ECP was reviewed again in November and approved by the CCB board on November 16th, 2020. The VLBI ECP is currently in the implementation phase.

The implementation plan has been divided into two phases, the first one affecting the updates to the documents that are needed for contracts (requirements and observatory establishment and delivery plan), and later during construction but before the completion of Array Assembly 2 milestone (to be confirmed), the update of the rest of the documentation, in a synchronised manner with other necessary SKA project changes.

Following are screenshots of the ECP-200033 VLBI form in the Configuration and Document Management for SKA Space contained in the SKA Project Confluence web-based corporate wiki.



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Pages / ... / Step 4.0 Perform Implementation and Verification 1 Jira link 196 views Edit Save for later Watching Share

ECP-200033 - VLBI L1 requirements alignment with SKA1-MID VLBI capability

Created by Miccolis, Maurizio, last modified by McMullin, Joe on Nov 29, 2020, viewed 196 times

Help page to complete this form: DRAFT PAGE: ECP Terms and Guidelines

eB Status: *(Completed by CM)* Jira Link(s):

| | | | | |
|---|---|---|---|---|
| ☑ Draft | ☑ Proposed | ☑ Expedited<br>☐ Approved | ☐ Rejected<br>☐ Complete<br>☐ Cancelled | TRKECP-112 - ECP-200033 - VLBI L1 requirements alignment with SKA1-MID VLBI capability<br>IMPLEMENTATION |

Outline of Change Impact: *(Completed by Originator)*

| ☐ Contract Change | ☐ Schedule Change | ☐ Budget Change | ☑ Technical/Engineering Change |
|---|---|---|---|
| ☐ Tier 1 Agreement<br>☐ Tier 2 Agreement<br>☐ Re-negotiated subcontract activity<br>☐ Adjustment or Correction to Details<br>☐ Other | ☐ Level 1 Milestone<br>☐ Level 2 Milestone<br>☐ Level 3 Milestone<br>☐ Proposed re-baseline of activities<br>☐ Slip in Schedule<br>☐ Gain in Schedule<br>☐ Other | ☐ Transfer of budget from one WBS Element or WP to another<br>☐ Transfer of budget to contingency<br>☐ Request budget from contingency<br>☐ Adjustment of budget with current month or next month<br>☐ Cost Increase<br>☐ Capex Cost Decrease<br>☐ Opex cost implication | ☑ Change to System Baseline<br>☑ Change to System Requirements (L1)<br>☑ Change to Product Requirements (L2 or below)<br>☐ Change to External ICDs<br>☐ Change to Element ICDs (L2)<br>☐ Change to Product ICDs (L3 and below)<br>☐ New Work Scope<br>☐ Correction to Technical Details<br>☐ Administrative Corrections |

| | |
|---|---|
| **TCR Panel** | @van Es, Andre @Lilley, Matthew @Labate, Maria Grazia @Hayden, Daniel @Cremonini, Andrea @Caiazzo, Marco @Swart, Gerhard @Santander-Vela, Juande @Bartolini, Marco |
| **CCB Members** | @McMullin, Joe @Stevenson, Tim , @Braun, Robert , @Ball, Lewis |
| **Other Stakeholders** | @van Zyl, Andreas @Schutte, Adriaan @Dewdney, Peter @Stringhetti, Luca, @Rees, Nick @Chrysostomou, Antonio @Lewis, Ben @Breen, Shari @Casson, Andrea @Laing, Robert @Dewdney, Peter |

Step 1.0 Submission

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## Step 1.0 Submission

☑ *(To be completed by Requestor)*

*** are **Mandatory fields** to complete before number allocation*

| | | | |
|---|---|---|---|
| Requester Name ** | Cristina Garcia Miro, Zsolt Paragi, Tao An, Cormac Reynolds | Requesting Organisation | on behalf of SKA VLBI SWG, JIVE |
| ECP Owner/Sponsor *(Jira Reporter field)*** | @Miccolis, Maurizio | | |
| Change Title ** | VLBI L1 requirements alignment with SKA1-MID VLBI capability | Associated Risk ID | |
| Description of Change ** | This ECP proposes to align one VLBI System level L1 requirement with the actual SKA1-MID VLBI capability. VLBI L1 rev. 12 requirements limit the number of VLBI beams and VLBI subarrays for SKA1-MID to a maximum of 4 but the SKA1-MID VLBI capability allows for many more VLBI beams (520) and subarrays for VLBI (16). It is proposed to modify one L1 requirement (SKA1-SYS_REQ-2689) and corresponding flowed down L2 TM requirements (3 requirements) to provide a maximum of 16 VLBI beams per subarray, and up to 16 subarrays for VLBI, but limiting to a total maximum of 46 concurrent VLBI beams, and therefore fulfill the SKA-VLBI science requirements as explained in "Reason for Change" paragraph.<br><br>The L1 requirement modification is proposed to be performed in such a way that the number of VLBI beams and VLBI subarrays is allowed to increase but the AIV and Science Commissioning activities will not be impacted.<br><br>In particular, the proposed increase in number of VLBI beams follows the SKA1-MID CBF Frequency Slice design (i.e. 2 VLBI beams per FSP), where the processing resources are limited to 26 Frequency Slice Processors, and therefore the increase of number of VLBI beams implies a necessary reduction of their bandwidth.<br><br>Additionally, the proposed change in number of VLBI beams per subarray (16) and number of subarrays (16) is an SKA1 capability that is already in place to support PST beamforming, and real-time beamforming calibration performance will be equivalent to the PST case.<br><br>The Observatory Software will be able to configure and control a larger number of VLBI beams and VLBI subarrays as it does for the PST observing mode, and the increase in the software capabilities is expected to have a negligible impact on the cost of its development.<br><br>None of the SKA1 ICDs will be impacted by this ECP as the FSA design is already described in the different interfaces. The increase in number of VLBI beams and subarrays complies with the data lines limitations imposed in the MID SDP-CSP ICD (300-000000-02) and the more restrictive SDP to VLBI MID ICD (SKA-TEL-SKO-0001061) with 4x100 GbE lines.<br><br>The SKA1 to VLBI External ICD will need to be updated to scale up the VLBI terminal in order to support higher recording data rates (from 2 VDIF recorders originally planned to up to 4 recorders with current technology). The VLBI terminal is to be provided by external funding, an SKA-VLBI Consortium that is currently being formed and is aware of this upgrade. Interfaces between the VLBI terminal to the SKA1-MID telescope do not change, as upgrades on number of recorders have been already contemplated in the VLBI terminal design. Consequently, the SKAO VLBI Requirements for the SKA1-MID SPC would need to be updated in terms of power required for the VLBI terminal (from 4 kW to 6.3 kW in recording/transfer mode) but the equipment space requirements already considered potential upgrades and no need further increase.<br><br>The proposed change will aditionally impact the SKA1 Design Baseline Description, the SKA1 Observatory Establishment and Delivery Plan, the SKA1 System Requirements Specification and the SKA1 TM Requirements Specification documents. | | |

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| | | | |
|---|---|---|---|
| Reason for Change ** | The SKA-VLBI Science Cases Portfolio has shown that SKA-VLBI science would greatly benefit if the number of VLBI beams provided per subarray is increased to at least 16 beams. Normally, the VLBI capability in SKA1-MID will configure one core subarray producing these VLBI beams. But for dual-band observations, up to 2 VLBI subarrays (dividing the core in two) will need to be configured, producing double number of beams (i.e. 16x2).<br><br>Additionally, the SKA-VLBI Operational Model has shown that to cover short spacings in the uv-coverage for the VLBI images, several individual SKA1-MID antennas would need to be included in the observations of the VLBI networks. Each of these individual antennas will provide just one VLBI beam, that corresponds to the SKA1-MID antenna primary beam. These individual antennas could be treated as independent VLBI subarrays formed with just one element, or a single subarray containing all of them. This capability is guaranteed by L1 requirements SKA1-SYS_REQ-2991 and 3136.<br><br>The maximum number of subarrays configured for VLBI is to be limited to 16, including the core or 2 subcores and a number of independent antennas. The maximum total number of VLBI beams formed concurrently from all 16 VLBI subarrays is to be limited to 46 (e.g. two subarrays producing 16 beams each and 14 individual antennas producing one beam each). | eB Change Number | ECP-200033 |
| Effectivity Date and Reason for this date: | | eB Link | https://ska-aw.bentley.com/SKAProd/Search/QuickLink.aspx?n=ECP-200033&t=6&d=Main%5ceB_PROD&sc=Global&i=view |
| Technical Issues and Trade-offs | This ECP does not result in changes in the SKA1 design, but implies minor additional budget costs in terms of extra labor and activities. | Change Classification ** | ☑ Class 1 (affects System requirements)<br>☐ Class 2<br>☐ Class 3 |
| Contract Award Number | | WBS WP Number(s) | |

Engineering Change:

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Engineering Change:

| SKAO Telescope Delivery Team(s) to assess | ☑ Observatory Level and Common System<br>☑ MID<br>☐ LOW | Submission Date: | 26 May 2020 |
|---|---|---|---|
| | | Supporting Documents? | ☐ No<br>☑ Yes, *(Please attach to page)* *ECP-200033-VLBI presentation*, *The SKA-VLBI Science Cases Portfolio*, *the SKA-VLBI Operational Model (upon request)*, *The L1 Traceability and Compliance matrix for VLBI*, *Details on VLBI interfaces to SKA Consortia, including the Revised VLBI requirements document* |

Functional Aspects Impacted

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Functional Aspects Impacted

| Impacted? | Comment | Impacted? | Comment |
|---|---|---|---|
| ☑ Requirements | Proposed to change following L1 requirement (rev. 11) and flowed down L2 TM requirements:<br>• **SKA1-SYS_REQ-2689: SKA1_Mid VLBI: number of beams**<br>SKA1_Mid, when commanded, shall produce a total of up to four VLBI beams, spread across one or more subarrays.<br>All four VLBI beams could be produced in a single subarray, or one in each of four subarrays. The total number of VLBI beams produced at any given time, across the entire telescope, is limited to four, and those four may be distributed as desired across the subarrays.<br>**Proposed description:**<br>SKA1_Mid, when commanded, shall produce **at least four** VLBI beams, spread across one or more subarrays.<br>**A maximum of 16** VLBI beams could be produced in a single subarray, or one in each of **16** subarrays. The total number of VLBI beams produced at any given time, across the entire telescope, is limited to **46**, ~~and those four may be distributed as desired across the subarrays.~~, **this capability being ultimately limited by SKA1 resources.**<br>• **SKA1-TM_REQ-444: Execute VLBI Observations**<br>TM shall support concurrent forming of up to 4 VLBI beams in the following ways:<br>a) by supporting up to 4 VLBI beams in the same Scheduling Block within the same Sub-array *,<br>b) by coordinating execution of up to 4 separate VLBI Scheduling Blocks concurrently, with each Scheduling Block executing on a different Sub-array that is configured for VLBI observing. | ☑ Performance | The performance of the real-time calibration for beamforming 16 VLBI beams produced from one subarray is equivalent to the PST science case (SKA1-SYS_REQ-2207).<br>For VLBI observations the SKA1-MID core could be divided into 2 subcores (2 VLBI subarrays) to support broadband or multi-band observations, providing up to 16 VLBI beams from each subarray. The beamforming performance for the case with 2 subarrays would be equivalent to the case with one subarray, just adding computing load, similar as observing in PST mode with 2 subarrays.<br>Apart from the core or subcores, rest of VLBI subarrays (up to 16) will be composed by just one SKA1-MID antenna, providing just one VLBI beam each. This case would be equivalent to the PST science case in terms of performance (SKA1-SYS_REQ-2207). |

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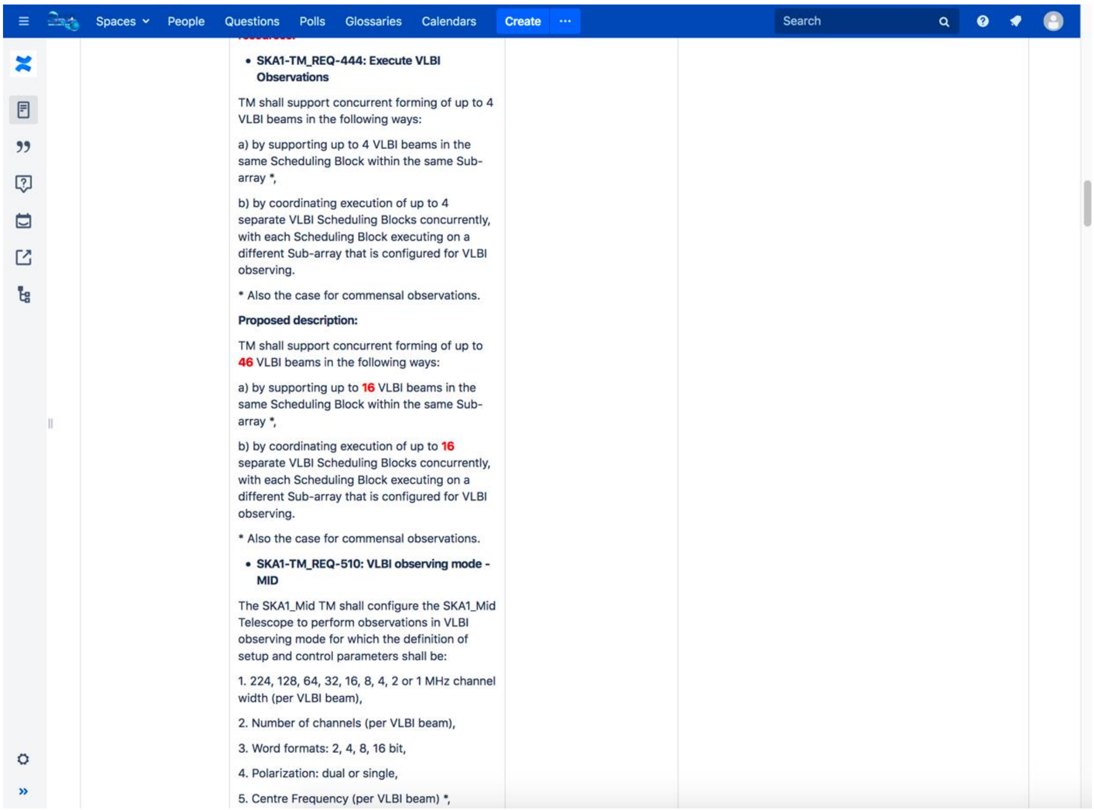

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- **SKA1-TM_REQ-444: Execute VLBI Observations**

TM shall support concurrent forming of up to 4 VLBI beams in the following ways:

a) by supporting up to 4 VLBI beams in the same Scheduling Block within the same Sub-array *,

b) by coordinating execution of up to 4 separate VLBI Scheduling Blocks concurrently, with each Scheduling Block executing on a different Sub-array that is configured for VLBI observing.

* Also the case for commensal observations.

**Proposed description:**

TM shall support concurrent forming of up to 46 VLBI beams in the following ways:

a) by supporting up to 16 VLBI beams in the same Scheduling Block within the same Sub-array *,

b) by coordinating execution of up to 16 separate VLBI Scheduling Blocks concurrently, with each Scheduling Block executing on a different Sub-array that is configured for VLBI observing.

* Also the case for commensal observations.

- **SKA1-TM_REQ-510: VLBI observing mode - MID**

The SKA1_Mid TM shall configure the SKA1_Mid Telescope to perform observations in VLBI observing mode for which the definition of setup and control parameters shall be:

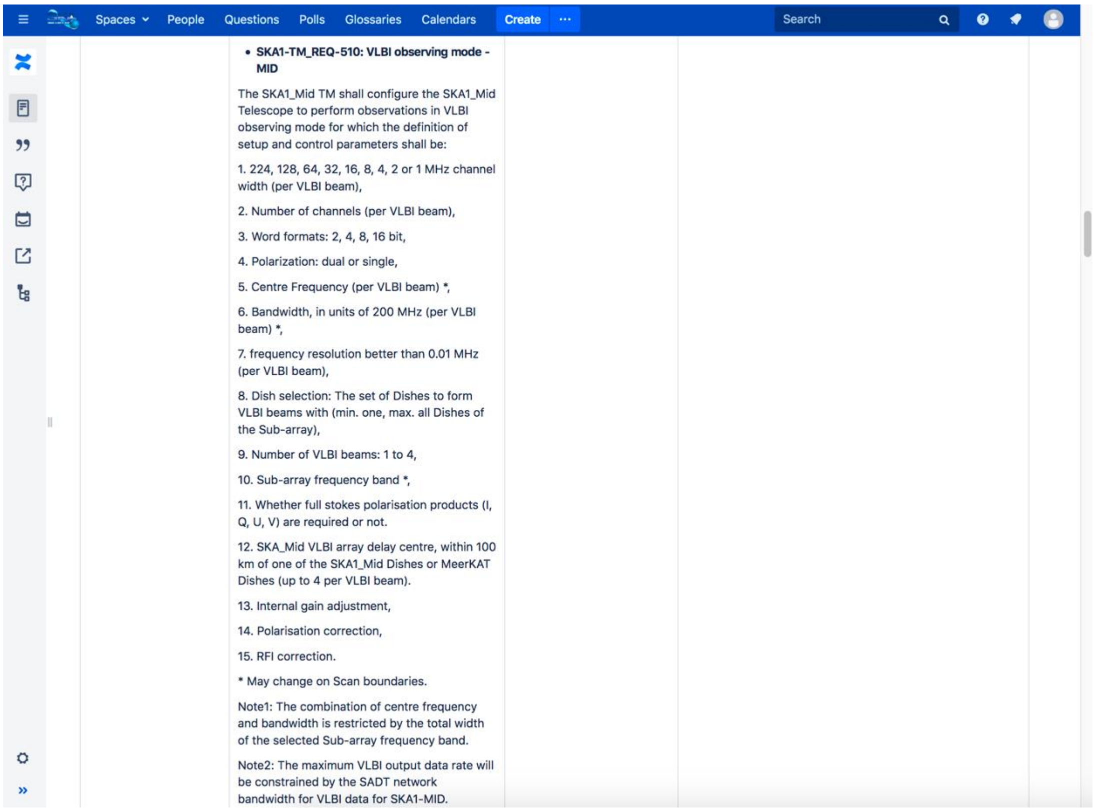
1. 224, 128, 64, 32, 16, 8, 4, 2 or 1 MHz channel width (per VLBI beam),

2. Number of channels (per VLBI beam),

3. Word formats: 2, 4, 8, 16 bit,

4. Polarization: dual or single,

5. Centre Frequency (per VLBI beam) *,



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- **SKA1-TM_REQ-510: VLBI observing mode - MID**

The SKA1_Mid TM shall configure the SKA1_Mid Telescope to perform observations in VLBI observing mode for which the definition of setup and control parameters shall be:

1. 224, 128, 64, 32, 16, 8, 4, 2 or 1 MHz channel width (per VLBI beam),

2. Number of channels (per VLBI beam),

3. Word formats: 2, 4, 8, 16 bit,

4. Polarization: dual or single,

5. Centre Frequency (per VLBI beam) *,

6. Bandwidth, in units of 200 MHz (per VLBI beam) *,

7. frequency resolution better than 0.01 MHz (per VLBI beam),

8. Dish selection: The set of Dishes to form VLBI beams with (min. one, max. all Dishes of the Sub-array),

9. Number of VLBI beams: 1 to 4,

10. Sub-array frequency band *,

11. Whether full stokes polarisation products (I, Q, U, V) are required or not.

12. SKA_Mid VLBI array delay centre, within 100 km of one of the SKA1_Mid Dishes or MeerKAT Dishes (up to 4 per VLBI beam).

13. Internal gain adjustment,

14. Polarisation correction,

15. RFI correction.

* May change on Scan boundaries.

Note1: The combination of centre frequency and bandwidth is restricted by the total width of the selected Sub-array frequency band.

Note2: The maximum VLBI output data rate will be constrained by the SADT network bandwidth for VLBI data for SKA1-MID.

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Note1: The combination of centre frequency and bandwidth is restricted by the total width of the selected Sub-array frequency band.

Note2: The maximum VLBI output data rate will be constrained by the SADT network bandwidth for VLBI data for SKA1-MID.

Note3: Restrictions will be enforced at the point that the Scheduling Block is created and amended.

**Proposed description:**

The SKA1_Mid TM shall configure the SKA1_Mid Telescope to perform observations in VLBI observing mode for which the definition of setup and control parameters shall be:

1. 224, 128, 64, 32, 16, 8, 4, 2 or 1 MHz channel width (per VLBI beam),
2. Number of channels (per VLBI beam),
3. Word formats: 2, 4, 8, 16 bit,
4. Polarization: dual or single,
5. Centre Frequency (per VLBI beam) *,
6. Bandwidth, in units of 200 MHz (per VLBI beam) *,
7. frequency resolution better than 0.01 MHz (per VLBI beam),
8. Dish selection: The set of Dishes to form VLBI beams with (min. one, max. all Dishes of the Sub-array),
9. Number of VLBI beams: 1 to **46**,
10. Sub-array frequency band *,
11. Whether full stokes polarisation products (I, Q, U, V) are required or not.
12. SKA_Mid VLBI array delay centre, within 100 km of one of the SKA1_Mid Dishes or MeerKAT Dishes (**for up to 16 VLBI arrays**).
13. Internal gain adjustment,
14. Polarisation correction,

12. SKA_Mid VLBI array delay centre, within 100 km of one of the SKA1_Mid Dishes or MeerKAT Dishes (**for up to 16 VLBI arrays**).
13. Internal gain adjustment,
14. Polarisation correction,
15. RFI correction.

* May change on Scan boundaries.

Note1: The combination of centre frequency and bandwidth is restricted by the total width of the selected Sub-array frequency band.

Note2: The maximum VLBI output data rate will be constrained by the SADT network bandwidth for VLBI data for SKA1-MID.

Note3: Restrictions will be enforced at the point that the Scheduling Block is created and amended.

- **SKA1-TM_REQ-574: Create Scheduling Block - VLBI restrictions**

TMO shall be able to configure a Scheduling Block to perform VLBI operations, allowing for at least the following parameters to be set:

1. Channel width: 512MHz, 256MHz, 128MHz, 64MHz, 32MHz, 16MHz, 4MHz, 1MHz (per VLBI beam),
2. Sampling rate: Nyquist frequency < frequency < factor of two oversampling for the selected bandwidth,
3. Word formats: 2,4,8 or 16-bit integer,
4. Polarization: Dual or Single,
5. Centre Frequency: 0.01MHz step selectable within frequency bounds of selected bandwidth (per VLBI beam),
6. Bandwidth (per VLBI beam),
7. frequency resolution (per VLBI beam),
8. independent delay centres (per VLBI beam): up to 4,

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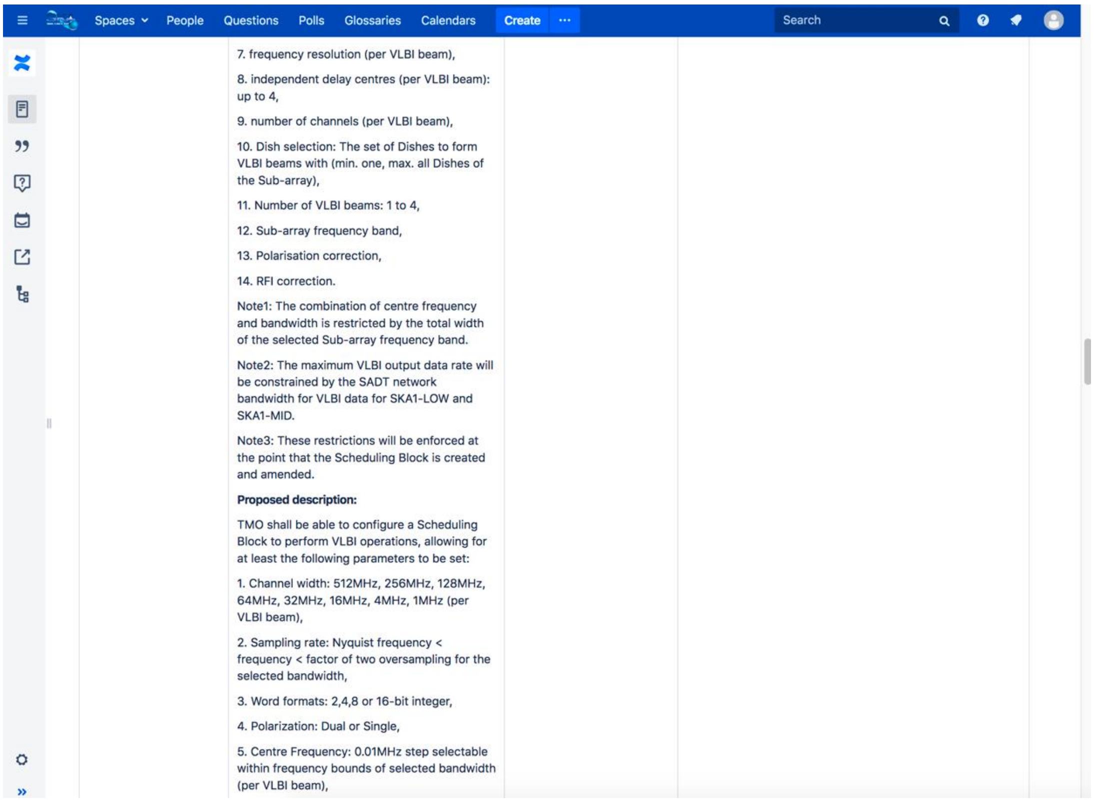

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7. frequency resolution (per VLBI beam),

8. independent delay centres (per VLBI beam): up to 4,

9. number of channels (per VLBI beam),

10. Dish selection: The set of Dishes to form VLBI beams with (min. one, max. all Dishes of the Sub-array),

11. Number of VLBI beams: 1 to 4,

12. Sub-array frequency band,

13. Polarisation correction,

14. RFI correction.

Note1: The combination of centre frequency and bandwidth is restricted by the total width of the selected Sub-array frequency band.

Note2: The maximum VLBI output data rate will be constrained by the SADT network bandwidth for VLBI data for SKA1-LOW and SKA1-MID.

Note3: These restrictions will be enforced at the point that the Scheduling Block is created and amended.

**Proposed description:**

TMO shall be able to configure a Scheduling Block to perform VLBI operations, allowing for at least the following parameters to be set:

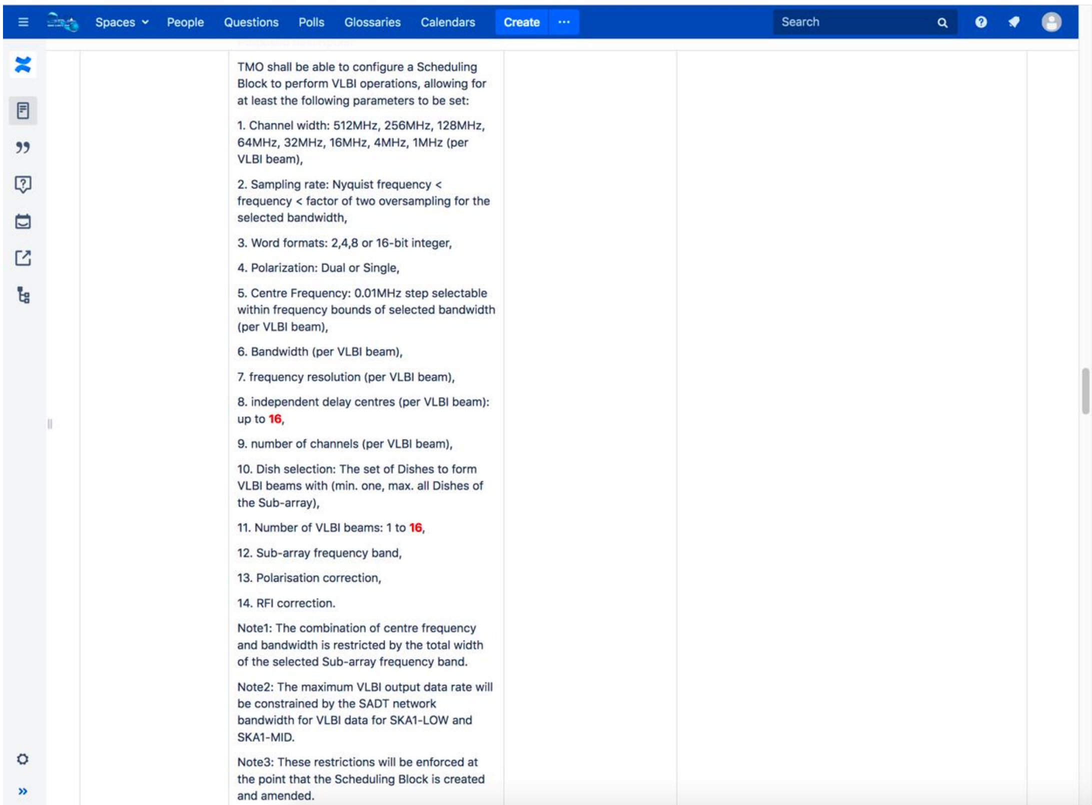
1. Channel width: 512MHz, 256MHz, 128MHz, 64MHz, 32MHz, 16MHz, 4MHz, 1MHz (per VLBI beam),

2. Sampling rate: Nyquist frequency < frequency < factor of two oversampling for the selected bandwidth,

3. Word formats: 2,4,8 or 16-bit integer,

4. Polarization: Dual or Single,

5. Centre Frequency: 0.01MHz step selectable within frequency bounds of selected bandwidth (per VLBI beam),



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TMO shall be able to configure a Scheduling Block to perform VLBI operations, allowing for at least the following parameters to be set:

1. Channel width: 512MHz, 256MHz, 128MHz, 64MHz, 32MHz, 16MHz, 4MHz, 1MHz (per VLBI beam),

2. Sampling rate: Nyquist frequency < frequency < factor of two oversampling for the selected bandwidth,

3. Word formats: 2,4,8 or 16-bit integer,

4. Polarization: Dual or Single,

5. Centre Frequency: 0.01MHz step selectable within frequency bounds of selected bandwidth (per VLBI beam),

6. Bandwidth (per VLBI beam),

7. frequency resolution (per VLBI beam),

8. independent delay centres (per VLBI beam): up to **16**,

9. number of channels (per VLBI beam),

10. Dish selection: The set of Dishes to form VLBI beams with (min. one, max. all Dishes of the Sub-array),

11. Number of VLBI beams: 1 to **16**,

12. Sub-array frequency band,

13. Polarisation correction,

14. RFI correction.

Note1: The combination of centre frequency and bandwidth is restricted by the total width of the selected Sub-array frequency band.

Note2: The maximum VLBI output data rate will be constrained by the SADT network bandwidth for VLBI data for SKA1-LOW and SKA1-MID.

Note3: These restrictions will be enforced at the point that the Scheduling Block is created and amended.

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| | | | |
|---|---|---|---|
| ☑ Physical and Functional Interfaces | None: OK but how much extra rack space budget do you need to be reserved in the MID CPF DRA at AA4 please?<br>Answer by @Cristina Garcia-Miro : MID-CBF design does not change due to this request, therefore equipment or rack space at the MID CPF does not change. The only equipment upgrade necessary for this ECP is the VLBI terminal dimensioning, located at the Science Processing Centre (SPC). | ☐ Construction/Production | None |
| ☐ EMC/RFI | None | ☑ Power | Power and thermal load requirements for the VLBI terminal at the SPC need to be upgraded from 4 kW to 6.3 kW (in recording/transfer mode). Consequently the SKAO VLBI power requirements for the SKA1-MID SPC need to be updated (SKA-TEL-SKO-0001067). Rack space requirements already contemplated a possible dimensioning of the VLBI terminal. The 2 racks originally planned are enough to allow for upgrades.<br>Question @Miccolis, Maurizio : Why is it assumed that the two additional racks and power consumption would be required in the SPC? Currently the Mid CBF is located in the KAPB?<br>Answer by @Cristina Garcia-Miro : the VLBI equipment is planned to be installed at the SPC, not at the CPF (KAPB). This equipment is assumed to be provided by an external SKA-VLBI consortium. The proposed upgrade of the VLBI terminal from 2 to 4 VDIF recorders implies to upgrade SPC power requirements for VLBI from 4kW to 6.3kW. The original rack space requested for VLBI at the SPC was already 2 racks to hold for possible upgrades, so there is no need for extra space at the SPC (apart from the 2 racks initially requested).<br>Just for clarification, MID-CBF design does not change due to this request, therefore equipment or rack space at the MID CPF (KAPB) does not change. |



| | | | |
|---|---|---|---|
| ☐ Integration Test Facility | None | ☑ Assembly and Verification | A minimum number of 4 VLBI beams and 4 VLBI subarrays would be considered for assembly and verification at System level, and 16 VLBI beams per subarray and 16 VLBI subarrays with up to 46 VLBI beams in total, at L2 level. TM would need to upgrade L2 verification requirements. NOTE: Many of the planned PST Assembly and Verification activities at System and L2 levels would also be applicable to the VLBI capability and will not need to be repeated. |
| ☑ Operations, Logistic Support | Science Operations would need to plan and schedule resources to support the increased number of VLBI beams and VLBI subarrays. | ☐ Health, Safety and Environment | None |

Product Delivery Teams Impacted

| Impacted? | Comment | Impacted? | Comment |
|---|---|---|---|
| ☑ MID Infrastructure | None: OK but how much extra rack space budget do you need to be reserved in teh MID CPF DRA at AA4 please?<br>Answer by @Cristina Garcia-Miro : MID-CBF design does not change due to this request, therefore equipment or rack space at the MID CPF does not change. The only equipment upgrade necessary for this ECP is the VLBI terminal dimensioning, located at the SPC. | ☑ MID Digitisation | To confirm that MID-CBF can provide 2 VLBI beams per FSP and can support 16 VLBI beams per subarray, for 16 subarrays, for a maximum of 46 concurrent VLBI beams, with bandwidths limited by the number of available FSPs (26).<br>To confirm that MID-CBF can perform VLBI beamforming in subarrays composed by just one MID antenna, providing just one VLBI beam, effectively the primary beam of the MID dish.<br>23 Jul 2020 Confirmed with email by MID Dish |
| ☐ | None | ☑ MID AIV / MeerKAT | A minimum number of 4 VLBI beams and 4 VLBI subarrays would be considered for AIV activities, without impact on roll-out plan, timing, CAPEX, etc. NOTE: Many of the planned PST AIV activities would be applicable to the VLBI capability and will not need to be repeated. |
| ☐ LOW Infrastructure | None | ☐ LOW Digitisation | None |
| ☐ LOW Field Node | None | ☐ LOW AIV | None |
| ☑ Networks and Computing | Networks and Computing have been dimensioned to support the full FSA design. Planned NSDN line for the VLBI terminal is not expected to be impacted (SADT to VLBI MID ICD, SKA-TEL-SKO-0001062), but a more detailed study should be accomplished whenever metadata format is fully defined (TM-VLBI ICD, SKA-TEL-SKO-0000932). | ☑ Science and Commissioning | Science and Commissioning activities would remain the same for the initial observing cycles and, from the observing cycle decided by the SKA1 Observatory, should include the enhanced VLBI capability support. |
| ☑ Observatory | Observatory software would need to configure | ☐ MeerKAT + | None |

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| | | | |
|---|---|---|---|
| ☑ Observatory Software | Observatory software would need to configure and control concurrently up to 46 VLBI beams in total, with a maximum of 16 VLBI beams per subarray, for a maximum of 16 subarrays.<br>This increase in the software capabilities is expected to have a negligible impact on the cost of its development. | ☐ MeerKAT + | None |

Division Impacted

| Impacted? | Comment | Impacted? | Comment |
|---|---|---|---|
| ☑ Operations | Science Operations would need to describe the VLBI observing mode and operations in the SKA1 Operations Plan. | ☑ Science | SKA Science to describe the SKA1 science capabilities for VLBI. |

Affected Documents that are impacted by the change

| Linked in eB *(CM to update)* | **Document Number **** | **Revision** | **Document Title** | **Comments** |
|---|---|---|---|---|
| ☑ | SKA-TEL-SKO-0000008 | 12 | SKA Phase 1 System Requirements Specification | One L1 requirement to be modified |
| ☑ | SKA-TEL-SKO-0001012 | 04 | SKA1 Operations Plan | SKA1 VLBI observing mode operations |
| ☑ | 601-000000-001 | 02 | SKA1 TM Observatory Requirements Specification | Three L2 TM requirements to be modified |
| ☑ | 303-000000-001 | 03 | SKA1 TM Mid Requirements Specification | Same three L2 TM requirements to be modified |
| ☑ | SKA-TEL-SKO-0001075 | 01 | SKA1: Design Baseline Description | SKA1 VLBI capability description |
| ☑ | SKA-TEL-SKO-0000116 | 01 | SKA1 to VLBI External ICD | VLBI terminal for SKA1-MID to be dimensioned |
| ☑ | SKA-TEL-SKO-0001067 | 01 | SKAO Requirements for the SKA1-MID Science Processing Centre | SPC requirements for VLBI terminal to be updated |

Affected Physical Items on the Product Breakdown Structure that are impacted by the change

Affected Physical Items on the Product Breakdown Structure that are impacted by the change

| Linked in eB *(CM to update)* | **Item Number **** | **Item Version** | **Item Description** |
|---|---|---|---|
| ☐ | N/A | | |
| ☐ | | | |
| ☐ | | | |
| ☐ | | | |
| ☐ | | | |

Contract Change:

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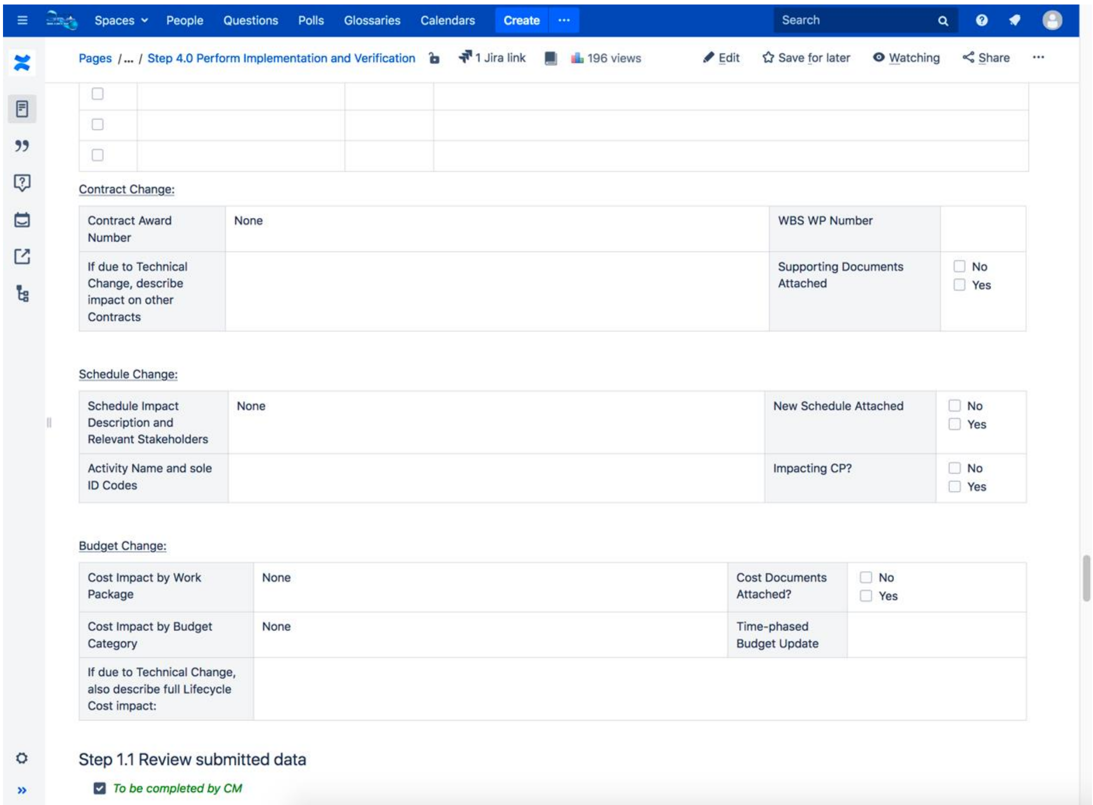

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Contract Change:

| | | | |
|---|---|---|---|
| Contract Award Number | None | WBS WP Number | |
| If due to Technical Change, describe impact on other Contracts | | Supporting Documents Attached | ☐ No<br>☐ Yes |

Schedule Change:

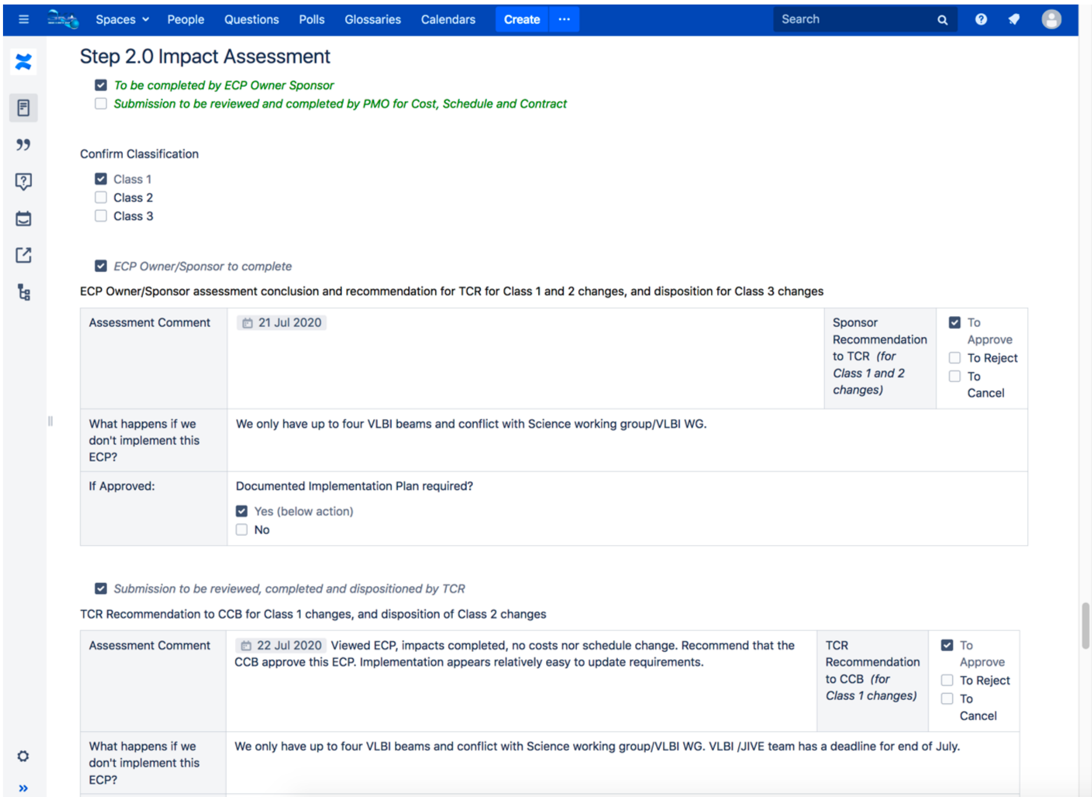
| | | | |
|---|---|---|---|
| Schedule Impact Description and Relevant Stakeholders | None | New Schedule Attached | ☐ No<br>☐ Yes |
| Activity Name and sole ID Codes | | Impacting CP? | ☐ No<br>☐ Yes |

Budget Change:

| | | | |
|---|---|---|---|
| Cost Impact by Work Package | None | Cost Documents Attached? | ☐ No<br>☐ Yes |
| Cost Impact by Budget Category | None | Time-phased Budget Update | |
| If due to Technical Change, also describe full Lifecycle Cost impact: | | | |

Step 1.1 Review submitted data

☑ *To be completed by CM*



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Step 2.0 Impact Assessment

☑ *To be completed by ECP Owner Sponsor*

☐ *Submission to be reviewed and completed by PMO for Cost, Schedule and Contract*

Confirm Classification

☑ Class 1

☐ Class 2

☐ Class 3

☑ *ECP Owner/Sponsor to complete*

ECP Owner/Sponsor assessment conclusion and recommendation for TCR for Class 1 and 2 changes, and disposition for Class 3 changes

| | | | |
|---|---|---|---|
| Assessment Comment | 21 Jul 2020 | Sponsor Recommendation to TCR *(for Class 1 and 2 changes)* | ☑ To Approve<br>☐ To Reject<br>☐ To Cancel |
| What happens if we don't implement this ECP? | We only have up to four VLBI beams and conflict with Science working group/VLBI WG. | | |
| If Approved: | Documented Implementation Plan required?<br>☑ Yes (below action)<br>☐ No | | |

☑ *Submission to be reviewed, completed and dispositioned by TCR*

TCR Recommendation to CCB for Class 1 changes, and disposition of Class 2 changes

| | | | |
|---|---|---|---|
| Assessment Comment | 22 Jul 2020 Viewed ECP, impacts completed, no costs nor schedule change. Recommend that the CCB approve this ECP. Implementation appears relatively easy to update requirements. | TCR Recommendation to CCB *(for Class 1 changes)* | ☑ To Approve<br>☐ To Reject<br>☐ To Cancel |
| What happens if we don't implement this ECP? | We only have up to four VLBI beams and conflict with Science working group/VLBI WG. VLBI /JIVE team has a deadline for end of July. | | |

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☑ *Submission to be reviewed, completed and dispositioned by TCR*

TCR Recommendation to CCB for Class 1 changes, and disposition of Class 2 changes

| | | | |
|---|---|---|---|
| Assessment Comment | 22 Jul 2020 Viewed ECP, impacts completed, no costs nor schedule change. Recommend that the CCB approve this ECP. Implementation appears relatively easy to update requirements. | TCR Recommendation to CCB *(for Class 1 changes)* | ☑ To Approve<br>☐ To Reject<br>☐ To Cancel |
| What happens if we don't implement this ECP? | We only have up to four VLBI beams and conflict with Science working group/VLBI WG. VLBI /JIVE team has a deadline for end of July. | | |
| If Approved: | Documented Implementation Plan required?<br>☑ Yes (below action)<br>☐ No | | |

## Step 3.0 Approval

☑ *To be completed by CCB*
☐ *Status to be noted/updated by PMO*
☑ *Status to be noted/updated by CM*

CCB Assessment and Disposition

| | | | |
|---|---|---|---|
| Assessment Comment | 23 Jul 2020<br>Q: JMM Queried the issues driving the timeline:<br>A: VLBI needs to know if we need 4 beams or incremental increase. They are limited to 46 beams concurrently. They have short time to 'pull things together', they would like to develop description as having 16 beams. Implementation will not be before construction proposal.<br>Q: JMM budget impact?<br>A: RL Nonzero budget impacts - activity in TM. After formal end of construction in commissioning. Will not change upfront construction costs.<br>CGM: Equipment will be provided by external consortium. External consortium establishment is in advanced stage. VLBI equipment was designed for this requirement.<br>Q: JMM: Cannot approve at this time due to budget/scope limits for CP, but we are enthsiastic. Is it hurtful if we defer for a period of time for later consideration. | CCB Decision | ☑ 23 Jul 2020 Decision Deferred until October 2020<br>16 Nov 2020<br>☑ Approve<br>☐ Reject<br>☐ Cancel |

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CCB Assessment and Disposition

| | | | |
|---|---|---|---|
| Assessment Comment | 23 Jul 2020<br>Q: JMM Queried the issues driving the timeline:<br>A: VLBI needs to know if we need 4 beams or incremental increase. They are limited to 46 beams concurrently. They have short time to 'pull things together', they would like to develop description as having 16 beams. Implementation will not be before construction proposal.<br>Q: JMM budget impact?<br>A: RL Nonzero budget impacts - activity in TM. After formal end of construction in commissioning. Will not change upfront construction costs.<br>CGM: Equipment will be provided by external consortium. External consortium establishment is in advanced stage. VLBI equipment was designed for this requirement.<br>Q: JMM: Cannot approve at this time due to budget/scope limits for CP, but we are enthsiastic. Is it hurtful if we defer for a period of time for later consideration.<br>A: CGM Jumping Jive can work on this as an 'assumption' until approval is gained. Not upgrading capability but upgrading requirements scope. Will bring back after CP.<br>C: LS Issue about 'Design changing Requirements' - not comfortable.<br>C: JMM How to handle change management of overachieved performance. Need to come back to this point when discussion happens on this ECP.<br>C: PD - We need to change requirements in order to ensure that the correlator construction will deliver this capability. Should not be an optional implementation.<br>D: JMM - bring back to CCB in October after CP.<br>16 Nov 2020 This ECP is approved. The modification provides requirement alignment between the SKA1 design capabilities and existing VLBI station capabilities and projected science program needs. In particular, the change in the number of beams is significantly less than the full SKA1 architectural ability and was chosen to be coordinated with the overall SKA1 implementation. We note that there are additional costs in bearing the modified data load but these are not borne by the SKA1 project (but are carried by the VLBI consortia).<br>For implementation, CGM will develop a Jumping Jive communication for review prior to publishing. | CCB Decision | ☑ 23 Jul 2020 Decision Deferred until October 2020<br>16 Nov 2020<br>☑ Approve<br>☐ Reject<br>☐ Cancel |
| Implementation Directives | Documented Implementation Plan required?<br>☐ Yes<br>☐ No | CCB Chairperson | @McMullin, Joe |

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## Step 4.0 Implementation

☐ Update eB *(CM)*

Affected Physical Items on the Product Breakdown Structure

| Linked in eB *(CM to update)* | Item Updated? | Item Number | Item Version | Item Description |
|---|---|---|---|---|
| ☐ | ☐ | | | |
| ☐ | ☐ | | | |
| ☐ | ☐ | | | |
| ☐ | ☐ | | | |
| ☐ | ☐ | | | |

Affected Documents Updated

| Linked in eB *(CM to update)* | Doc Updated? | Document Number | Revision | Document Title | |
|---|---|---|---|---|---|
| ☑ | ☐ | SKA-TEL-SKO-0000008 | 12 | SKA Phase 1 System Requirements Specification | One L1 requirement to be modified |
| ☑ | ☐ | SKA-TEL-SKO-0001722 | 01 | SKA1 Observatory Establishment and Delivery Plan | SKA1 VLBI observing mode operations |
| ☑ | ☐ | 601-000000-001 | 02 | SKA1 TM Observatory Requirements Specification | Three L2 TM requirements to be modified |
| ☑ | ☐ | 303-000000-001 | 03 | SKA1 TM Mid Requirements Specification | Same three L2 TM requirements to be modified |
| ☑ | ☐ | SKA-TEL-SKO-0001075 | 01 | SKA1: Design Baseline Description | SKA1 VLBI capability description |
| ☑ | ☐ | SKA-TEL-SKO-0000116 | 01 | SKA1 to VLBI External ICD | VLBI terminal for SKA1-MID to be dimensioned |
| ☑ | ☐ | SKA-TEL-SKO-0001067 | 01 | SKAO Requirements for the SKA1-MID Science Processing Centre | SPC requirements for VLBI terminal to be updated |

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Implementation Action List

| | Action Description | Who | When |
|---|---|---|---|
| ☐ | @Miccolis, Maurizio to insert description of implentation plan 23 Jul 2020<br>The changes of SKA capabilities associated to this ECP shall be considered in the Construction. Therefore I suggest that only documents needed for Contract are affected in a first phase of implementation<br>• SKA-TEL-SKO-0000008 - SKA Phase 1 System Requirements Specification<br>• SKA-TEL-SKO-0001722 - SKA1 Observatory Establishment and Delivery Plan<br>• SKA-TEL-SKO-0001067 - SKAO Requirements for the SKA1-MID Science Processing Centre | | |
| ☐ | All other technical changes to the documentation will be affecting later stages of Construction. Therefore I suggest that the updates to those documents are implemented as soon as convenient, only when other siginficant modifications will become necessary.<br>In any case the documentation shall be updated before the completion of AA2 (TBC).<br>• 601-000000-001 - SKA1 TM Observatory Requirements Specification<br>• 303-000000-001 - SKA1 TM Mid Requirements Specification<br>• SKA-TEL-SKO-0001075 - SKA1: Design Baseline Description<br>• SKA-TEL-SKO-0000116 - SKA1 to VLBI External ICD | | |

Like Lilley, Matthew likes this

No labels

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# ANNEX 4: SKA-VLBI Capability Implementation - Observing scenarios for SKA1-MID

## ANNEX 4.1: Scenario 1 - One core subarray producing one VLBI beam

In this simplest scenario, one core subarray is phased-up to produce only one VLBI beam, pointed in the same direction as the antennas in the subarray. Therefore, the beamforming will be performed for the boresight direction. The phasing up of the beam could be performed using a phasing cycle approach, like the one adopted by the JVLA or ALMA (e.g. TelCal system, Matthews et al. 2018, RD120), defining an observing cycle between a phasing calibrator and the target. Depending on the target characteristics, no antenna movement would be necessary if the target itself can be used as a phasing calibrator. On the contrary, a phasing calibrator closest to the target as possible should be chosen to minimize antenna movement and systematic errors in the beamforming process, mostly caused by atmospheric effects.

For boresight beamforming on SKA1-Mid, the Telescope Manager (TM) computes the theoretical delay tracking models for the boresight position to point the antennas in the subarray (and the VLBI beam). During the phasing scan, the correlator-beamformer (CBF) produces boresight SKA visibilities (and boresight VLBI visibilities with reduced frequency resolution) and provides them to the Science Data Processor (SDP) for real-time calibration for boresight beamforming. The antenna-based gains determined by SDP on the phasing calibrator are sent to TM and applied to the target scan by the correlator-beamformer (CBF) that will phased-up the subarray based on this information for coherent beamforming. For VLBI the leakage polarisation correction for the boresight direction is performed at the frequency slice level before beamforming. No Doppler corrections are applied to VLBI beamforming (both components, individual antennas component and global array component).

The phasing cycle for VLBI will be defined in the VEX file. The VEX 2.0 standard incorporates a scan intent definition to be able to define the type of scan, phasing calibrator or target, in the phasing cycle. The VEX file will also incorporate all usual VLBI calibration scans, for fringe finding, bandpass calibration, amplitude and phase calibration, pointing, etc. For SKA1-Mid only several scans on a standard flux calibrator could be included for flux calibration of the subarray.

The latency used for the phasing cycle would depend on many factors: the observing frequency, the core subarray size, weather conditions and sun activity during the observation, the elevation of the antennas, the characteristics of the phasing calibrator, such as the flux density (and observed bandwidth) and separation from the target, etc.

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Based on the JVLA experience that is applicable to SKA1-Mid, it is recommended to use 1-minute scans for phasing, using a point-like calibrator for the JVLA's subarray synthesized beam, as close as possible to the target, with a flux density > 100 mJy for 1-12 GHz frequencies and > 350 mJy for 12-45 GHz. As for the phasing latency, for the different JVLA configurations:

> C & D configuration: that is equivalent to 1.5 and 0.5 km SKA1-Mid radius core, 20-30 minutes are used for lower frequencies (equivalent to Band 1,2, 5a) and 10-20 minutes at higher frequencies (Band 5b).
>
> A & B configuration: that is equivalent to 18 and 5.5 km SKA1-Mid radius core, 5-10 minutes are used for lower frequencies (equivalent to Band 1,2, 5a) and 2-5 minutes at higher frequencies (Band 5b).

For SKA1-Mid the typical core radius to be phased-up would be about 4 km, which is equivalent to JVLA configuration B, with 10 minutes for lower frequencies and 5 minutes for higher ones.

The recommendations are to follow a conservative approach, as not frequent enough phasing scans would lead to a SNR loss that cannot be recovered in post-processing. Proper planning would be necessary to mitigate weather and sun unpredictable impact, and it would be better to observe at night and winter, avoiding sunrise and sunset, as far as possible. As for RFI, whenever possible, the subbands should be defined as free as possible of RFI to avoid impact on the beamforming process.

Kudale & Chengalur, 2017 (RD121, Fig. A.2) using the GMRT have measured at 607 MHz the SNR degradation experienced on a pulsar beam that is only phased-up at the beginning of the observation and is let to degrade (purple), comparing with the case of a beam that is re-phased every 4 minutes (green), keeping its SNR constant. The degradation experienced is compatible with Kolmogorov type turbulence in the ionosphere. This example shows how often the beam would need to be re-phased to keep the SNR above a reasonable value for that particular frequency, which would be equivalent to SKA1-Mid Band 1.

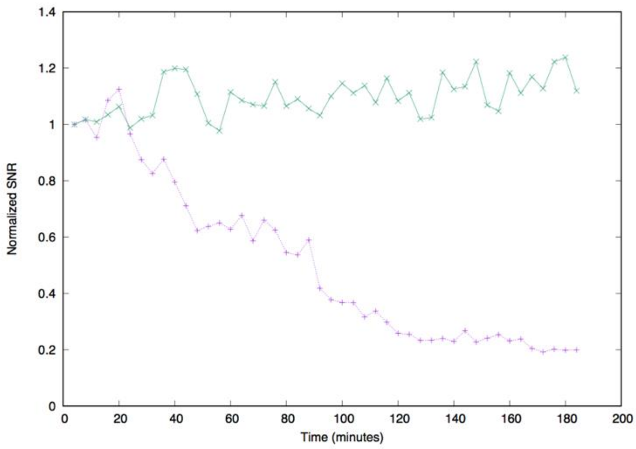


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**Figure A.2. SNR degradation for a GMRT pulsar beam at 607 MHz compared with re-phasing every 4 minutes (extracted from Kudale & Chengalur, 2017, RD121).**

SKA1-Mid has been designed for continuous coherent beamforming to control the SNR degradation on the beams continuously. This is possible as CBF correlation and beamforming, and SDP real-time calibration happens in a simultaneous and synchronised way, orchestrated by TM. For SDP processing, we may have different alternatives to choose the model to derive the gains, using the target if appropriate, or a field calibrator within the FoV, or the local sky model (LSM) either measured during the observation or previously during another observation. If none of these models is acceptable, antenna movement will be required to observe a proper phasing calibrator.

The SKA1 system would be able to cope with solutions provided as fast as every 10 seconds, but the phasing strategy and latency will depend on the science project characteristics and the SKA1-Mid overheads, mostly due to the SDP real-time calibration processing for that particular model.

## ANNEX 4.2: Scenario 2 - One core subarray producing multiple VLBI beams (2-16)

For the second scenario, one core subarray is phased-up to produce more than one beam, from 2 up to 16 VLBI beams. This case will be used to support targeted, survey and relative astrometry observing modes.

The scenario necessarily involves boresight and off-boresight beamforming. Again, there are two alternatives for the observing strategy, without antenna movement if there is a suitable phasing calibrator in the target field placing the target or calibrator at the boresight position, or with antenna movement if there is not any good calibrator.

CSP-Mid is able to beamform any type of tied-array beam anywhere within the primary beam of the largest receptor used, for the highest observed frequency. For a Mid antenna this means for each frequency band:

Band 1: +/-1.82 deg
Band 2: +/-0.67 deg
Band 3: +/-0.39 deg
Band 4: +/-0.23 deg
Band 5a: +/-0.14 deg
Band 5b: +/-0.08 deg

A study of the availability of suitable phasing calibrators depending on the frequency and FoV will be required. Rioja et al. (2020, table 6.1, RD026) have performed a study to find suitable calibrators for phase referencing with SKA-VLBI type baselines, that necessarily does not

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correspond with the same requirements as for phasing calibrators but can be considered as a starting point.

Each CSP-Mid frequency slice processor (FSP) processes the same frequency slice from all the antennas in the subarray and is able to provide 2 independent VLBI beams with different pointings within the primary beam and low-frequency resolution VLBI visibilities centred at one of the beams. Therefore, in VLBI mode up to 26 different phase centres within the antennas' primary beam can be used (for this particular use case a maximum of 16, corresponding to the maximum number of beams). This CSP-Mid characteristic allows for a different approach for phasing for VLBI than for pulsar search and pulsar timing (PSS/PST), having the VLBI mode a built-in solution for the determination of the direction-dependent corrections, that the other modes do not have.

For boresight and off-boresight beamforming on SKA1-Mid, the Telescope Manager (TM) computes the theoretical delay tracking models for the boresight and off-boresight positions to point the antennas in the subarray and all the VLBI beams within the primary beam. During the phasing scan, the correlator-beamformer (CBF) produces boresight SKA visibilities and boresight/off-boresight VLBI visibilities and provides them to the Science Data Processor (SDP) for real-time calibration for boresight/off-boresight beamforming. The antenna-based gains determined by SDP on the different phase centres are sent to TM and applied to the target scan by the correlator-beamformer (CBF) that will phased-up the subarray based on this information for coherent beamforming. For VLBI the leakage polarisation correction for the boresight and off-boresight directions is performed at the frequency slice level before beamforming. Doppler is not corrected for VLBI beamforming.

There are different possibilities for phasing, from the simplest to the most complicated, taking into account or not direction-dependent effects:

1. Place the phasing calibrator (or target if appropriate) at boresight and use VLBI/SKA boresight visibilities to determine the antenna-based gains and apply them to both bore and off-bore VLBI beams, under isoplanatic assumption.
2. Same as before but use the approach used for PSS/PST off-boresight beamforming using the a-priori differential phases calculated by TM.
3. Use SKA or VLBI visibilities for boresight and the LSM model (current or previous) to determine antenna-based gains and apply to bore and off-bore VLBI beams, under isoplanatic assumption or using PSS/PST approach.
4. For more complex target fields and lower observing frequencies use VLBI visibilities at multiple phase centres (several phasing calibrators) to determine antenna-based direction-dependent gains and perform a 2D interpolation to apply to different targets directions.
5. Alternatively, to the previous option, instead of using VLBI visibilities, direction-dependent effects could be determined using the SKA boresight visibilities and apply methods such as LEAP (Rioja et al. 2018, RD023) to correct for direction-dependent effects in the visibility domain.

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For this scenario, the same considerations as for Scenario 1 need to be made with respect to phasing cycle latency, but in this case more than one phasing calibrator could be used, and therefore their distances to the target could be increased, relaxing the requirements.

## ANNEX 4.3: Scenario 3 - Two core subarrays producing multiple VLBI beams (2-16)

For broadband (e.g. Band 5a and 5b simultaneously) or multi-band (e.g. Band 2 and Band 5 simultaneously) observations for targeted, survey and relative astrometry observing modes it would be necessary to configure at least two subarrays providing the same number of VLBI beams, from 2 to 16 beams each. These subarrays will be made of partitions of the core.

Scientific requirements will define the size (number of antennas and baseline lengths) of each subarray for example to match VLBI beams FoV vs. frequency or match sensitivity taking into account the different observing bandwidths.

In general, both subarrays will observe simultaneously the same area of the sky, with the same phasing cycle defined for the most restrictive frequency band. Therefore, the same scheduling block (SB) could be used to configure both subarrays, except for the frequency configuration parameters.

But there could be more possibilities for the observing strategy subject to the VLBI networks capabilities in terms of broadband receivers, configuration of different band VLBI subnetworks, etc.

## ANNEX 4.4: Scenario 4 - multiple individual antennas (up to 16) providing one VLBI beam each

This scenario adds up to 16 individual SKA1-Mid antennas (i.e. outrigger elements) to the VLBI networks to improve short and intermediate spacings in the uv coverage for the VLBI observations. The addition of different size antennas to the VLBI arrays (SKA1 vs. MeerKAT antennas) is not a problem as nowadays most VLBI networks are heterogeneous. Thanks to this observing mode the SKA-VLBI capability will rely less on SKA data products for the calibration of the VLBI products, freeing up resources.

Each outrigger SKA1-Mid antenna forms one independent subarray with just one element that provides one VLBI beam, effectively the primary beam of the antenna, channelised and properly formatted in VDIF format. All these subarrays will observe the same sky direction, with exactly the same sequence as the VLBI antennas (defined in the VEX file) without the need to add phasing scans, as no phasing or processing of the visibilities would be required.

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During the study of this scenario, it was confirmed by the SKAO that SKA1-Mid will also be able to define a unique subarray containing all the outrigger antennas, simplifying the operation.

## ANNEX 4.5: Scenario 5 - Two core subarrays producing multiple VLBI beams (2-16) and 14 individual antennas providing one VLBI beam each

This last scenario is the most complicated one presenting a combination of previous cases, with the aim to provide sensitive pencil SKA-VLBI beams for a dual-band or broadband observation and improve the short/intermediate uv spacings including individual SKA1-Mid antennas to the VLBI networks.

At least 4 subarrays would be needed to support these observations, two core subarrays providing the pencil beams and two subarrays containing the outrigger antennas configured for each observing band. All subarrays will observe the same sky direction, with exactly the same sequence as the VLBI antennas (from the VEX file) but the core subarrays will also include the phasing scans, defined for the most restrictive band, as described in previous scenarios. The total number of simultaneous VLBI beams would be 46 (16x2 + 14).

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# ANNEX 5: SKA Contact magazine

## SETTING THE WORLD'S EYE ON THE SKY WITH THE SKA

BY CRISTINA GARCIA-MIRO (JIVE), ZSOLT PARAGI (JIVE), ANTONIO CHRYSOSTOMOU (SKAO), GINA MAFFEY (JIVE)

**Back in October, SKA HQ played host to a major scientific workshop, which explored how the SKA can be integrated with existing Very Long Baseline Interferometry (VLBI) networks across the world.**

"SKA will have a VLBI capability" – with this strong statement, Prof. Phil Diamond, SKA Director-General began the SKA-VLBI Key Science Projects and Operations workshop* to explore VLBI in the SKA context. By remotely combining the data from radio telescopes observing the same source at the same time, VLBI offers the highest possible imaging resolution in astronomy. In light of this, ensuring that the future SKA Observatory is VLBI-enabled is a priority for the SKA Organisation.

"The black hole image unveiled by the EHT collaboration this year demonstrated the potential and power of a global VLBI effort," said Antonio Chrysostomou, SKAO Head of Science Operations. "The size of the SKA will have a significant impact on the science that we can do with this technique. This is an exciting prospect."

During the course of the week, 65 scientists from 18 different countries came together to share their enthusiasm for the scientific possibilities that VLBI brings. Sessions at the workshop were organised to focus on SKA high priority science objectives – providing snapshots of current research on wide ranging topics such as Active Galactic Nuclei (AGN), Fast Radio Bursts (FRBs), stellar birth and evolution, exoplanets, and the prospect for the inclusion of African telescopes in SKA-VLBI.

A common theme across the talks was the need for very high sensitivity in VLBI observations. To tackle this challenge, SKA telescopes will need to be included in existing VLBI arrays – which in turn, will present interesting technical hurdles in the coming years.

During the workshop, four working groups sought to practically address some of the highlighted challenges and the subsequent discussions were extremely fruitful. Participants grappled with how to realise the ambitious science objectives, but a highlight was the realisation that it may be possible to achieve extremely precise astrometric observations with SKA-VLBI – down to 1 micro-arcsecond!

### DID YOU KNOW?

One arcsecond equates to about 2km on the Moon's surface. A micro-arcsecond is 1 million times smaller than this, around 2mm. That means that using VLBI, we would be able to resolve and see a strand of spaghetti on the Moon!

The workshop was led by the Joint Institute for VLBI ERIC (JIVE). As the central organisation in the European VLBI Network (EVN), JIVE offers both technical and scientific support to the VLBI community across the globe. Former Director of both JIVE and the SKA, Richard Schilizzi, closed the workshop with a reminder of the inspiring legacy of collaboration across the community that SKA-VLBI can build on.

One of the SKA's catchphrases is "the future of radio-astronomy has already begun". At the end of the workshop, one thing was clear: SKA-VLBI can play a significant role in defining that future.

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