JUMPING JIVE

Project ID: 730884

WP10: VLBI with the SKA

Deliverable:	D10.3 Portfolio of SKA-VLBI Science Cases
Lead beneficiary:	JIV-ERIC and Square Kilometre Array Phase 1 Project
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Dissemination level:	VLBI Science Working Group members, SKA Organisation Operations Planning Group, SKA Organisation Science Group, VLBI Consortium (lead by JIV-ERIC Institute).

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1 Executive Summary

JUMPING JIVE WP10 deliverable (D10.3) "Portfolio of SKA-VLBI science cases" presents a wide variety of projects prepared by 30 different teams of scientists that fully exploit the SKA1 telescopes' VLBI capability and cover most of the science that will be realized thanks to the high angular resolution and sensitivity provided by SKA-VLBI.

This has greatly expanded the previous SKA1 Scientific Use Cases published in 2016 [RD4], where only 6 projects requested VLBI, and none for SKA1-LOW telescope as the VLBI capability was not included in its design at that time.

The science use cases are very useful in many different ways: they inform the design of the SKA1 Observatory with respect to the capabilities needed, requirements, discover limitations imposed by the design, etc.; they also inform to the SKA1 Science Operations Planning group about the observing strategies and modes, science data products, issues to be determined or solved, etc.; and lastly, the exercise has been very productive to develop a community with knowledge of the SKA-VLBI capability and all its potential, in preparation for future SKA-VLBI Key Science Projects.

2 Introduction

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

Task 1: Define the SKA-VLBI Operational Model:

- Ensure adequateness of SKA1 System Level requirements for SKA-VLBI science.
- Define VLBI Interfaces with key SKA1 Elements: Central Signal Processor (CSP), Telescope Manager (TM), Signal and Data Transport (SaDT) and Science Data Processor (SDP).
- Prepare a Verification and Commissioning plan for integration of SKA1 with global VLBI networks.
- Develop a framework for proposal handling, time allocation and scheduling, observation management, data delivery and data rights.

Task 2: Develop of Global Science Cases:

- Revise and update the SKA-VLBI use cases.
- Develop ideas and strategies for Key Science Projects (KSPs), with the support of the SKA VLBI science working group.
- Organise a SKA-VLBI Science workshop.

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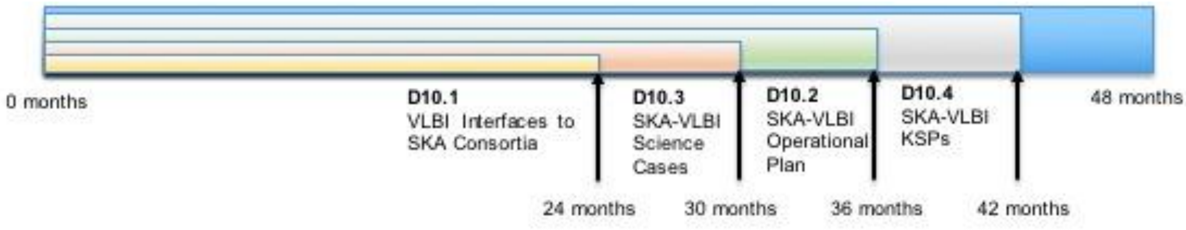

Figure 1. JUMPING JIVE WP10 deliverables schedule

The work package WP10 provides four main deliverables, scheduled in a period of 42 months (Figure 1). The technical realization of VLBI observations with the phase 1 SKA telescopes SKA1-LOW and SKA1-MID [RD1, RD2] were described in the deliverable D10.1. This report is the third deliverable D10.3, “Portfolio of SKA-VLBI Science Cases”, where we summarise the first stage of our work towards defining possible SKA-VLBI science projects. We do this using Science Use Case description forms (updated to include VLBI requirements) provided by the SKAO. These forms inform the SKA consortia about the various ways scientific projects want to use the instrument, helping to the requirements definition [RD3]. By evaluating the forms and matching the requirements to CSP and SDP resources we can also see if a certain project would run into severe limitations in any of these components. It also helps the user community to think creatively about using the available resources for VLBI at the SKA. Therefore, we expect that the SKA-VLBI Use Cases we present here will develop considerably in the future. The SKA1 Scientific Use Cases document [RD4, 2016] had only six Science Use Cases that requested the VLBI capability out of a total of 58 cases. It was the VLBI scientist's main role to initiate the discussions with the VLBI SWG members and the VLBI community regarding the preparation of additional VLBI science cases, especially for the SKA1-LOW telescope.

The strategy to define the science program was the following: we have presented the SKA-VLBI capabilities and advertised the possibility to formulate SKA-VLBI Key Science Programs in presentations at various forums. These included the 14th European VLBI Network Symposium and Users Meeting in Granada, Spain (October 2018), the SKA General Science Meeting and Key Science Workshop in Alderley Edge, United Kingdom (April 2019), and SKA science working group discussions; two papers describing the SKA-VLBI technical capabilities and the possible KSPs have been published online (Garcia-Miro et al. 2018 [RD5] [arXiv:1903.08627], Annex 3; Paragi et al. 2018 [RD6] [arXiv:1901.10361]); we then approached the community, prepared and shared with them a SKA-VLBI science performance document as a guideline for science cases preparation (Annex 2), and asked for SKA-VLBI Use Case ideas and worked together with a number of groups iteratively to formulate their use cases, which are presented in Annex 1.

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3 JUMPING JIVE WP10 Deliverable D10.3 description

This deliverable D10.3, “Portfolio of SKA-VLBI Science Cases”, consists of the following documents:

- Outcomes on the Portfolio of SKA-VLBI Science Cases (present report)
- Portfolio of SKA-VLBI Science Cases (Annex 1)
- SKA-VLBI science performance document (Annex 2)
- SKA-VLBI Capability, 14^{th} EVN Symposium proceedings paper (Annex 3)

4 SKA-VLBI Science Performance

Annex 2 consists of the SKA VLBI science performance document which we put together to guide the preparation of the different science cases. This document summarizes the SKA Phase 1 VLBI capability and the science performance that will be achieved for different VLBI observing configurations. The information it contains enables members of the VLBI science community to estimate the performance of the SKA receivers as part of a global VLBI network, at a range of different frequencies, and therefore plan use cases accordingly.

The science performance document is based on the current estimates of the performance anticipated for the SKA1 Design Baseline and described in detail in [RD7]. Calculations are made for the frequency range 50-350 MHz for SKA1-LOW and 350 MHz-50 GHz for SKA1-MID, regardless of the deployment baseline plans for the different SKA1 receivers. The different sections explain the calculations necessary to compute the System Equivalent Flux Density (SEFD) for SKA1-MID and LOW VLBI beams for different subarray configurations and observing frequencies. The baseline sensitivities were calculated assuming a 100m class remote telescope, with typical characteristics detailed in the EVN status tables [RD8]. Baseline sensitivities of several tens of μJy/beam are achieved with SKA1-MID for the various configurations throughout the frequency bands (Fig. 2), while several hundreds of μJy/beam are achieved with SKA1-LOW (Fig. 3).

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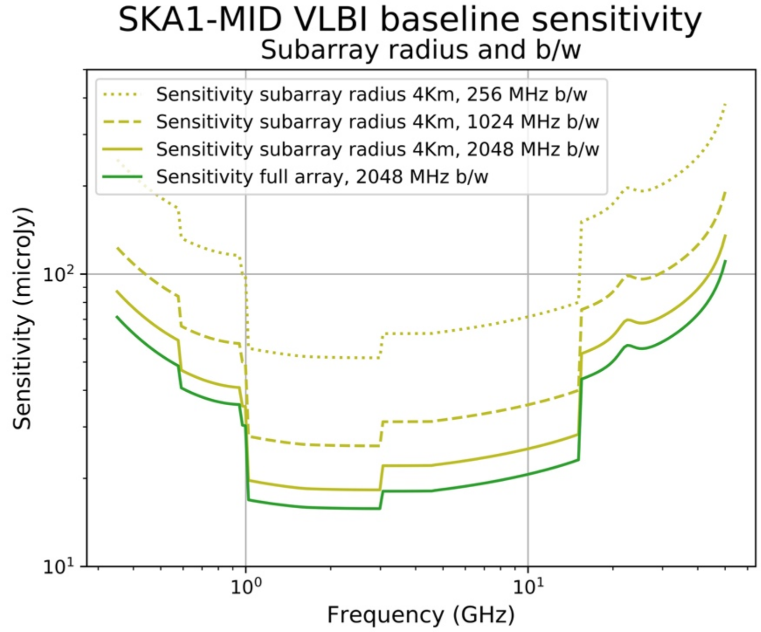

Figure 2. Baseline sensitivity for different SKA1-MID subarrays configurations and a 100m class remote telescope, for different observing bandwidths and 60sec integration times (1-sigma), and best observing conditions at zenith.

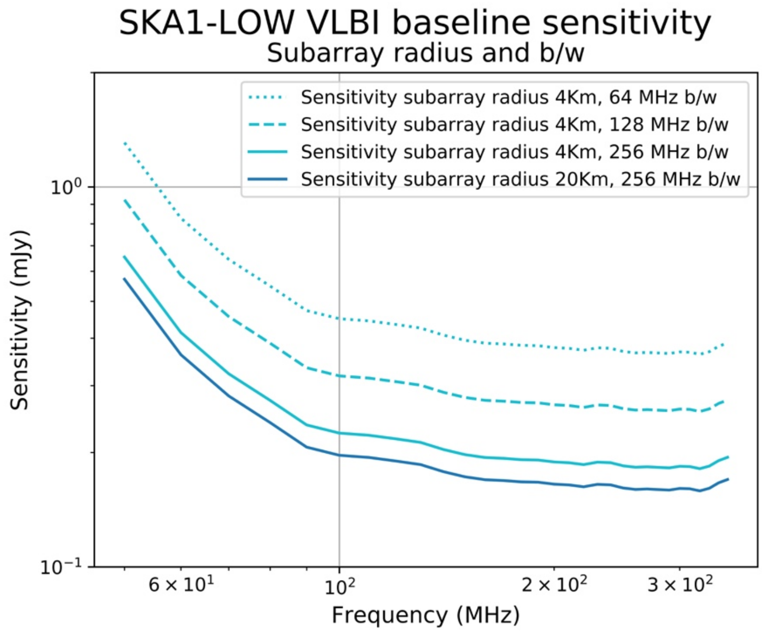

Figure 3. Baseline sensitivity for different SKA1-LOW subarrays configurations and a 100m class remote telescope, for different observing bandwidths and 60sec integration times (1-sigma), and best observing conditions at zenith.

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5 SKA-VLBI Science Cases

Following is the collection of SKA-VLBI science cases presented in this report. A total of 30 science cases are presented, 7 for VLBI with SKA1-LOW, 22 for SKA1-MID and one describing an observing strategy common for both. Previously, the SKA1 Scientific Use Cases document [RD4] contained only 6 Science Use Cases that requested the VLBI capability out of a total of 58 cases, and none for SKA1-LOW, since at the time of publication (2016) the SKA1-LOW telescope did not have the VLBI capability implemented in its design. These 6 original VLBI science cases have been updated in view of the detailed design presented and assessed in the Critical Design Reviews of the different SKA1 telescope elements and presented as part of this collection. Annex 1 details the individual pro-formas for each of the science cases.

In the table below (Table 1) we enumerate the 30 use cases. If the lead author/s is a member of the VLBI working group (associate or core) this is indicated. The short name links to the full science use case form in the Annex 1 of this document.

Title	Short name and hyperlink	Authors
	New VLBI science cases with SKA1-LOW telescope	
Jets from low mass Young Stellar Objects at very low frequencies	**YSO-LOW**	Ainsworth, Scaife
Inhomogeneous supernovae at low frequencies	**SNe-LOW**	Chandra, Bjornsson, Perez-Torres, et al.
SKA-Low precise astrometry of Low-Frequency Pulsars	**PSR-ASTR-LOW**	Dodson (core), Rioja, Sobey
Precise astrometry for exoplanets detection with SKA1-LOW and VLBI	**EXOPL-ASTR-LOW**	Guirado, Dodson (core), Jiménez-Serra, Rioja
HI absorption at sub-kpc scales in normal and active galaxies at high redshifts	**HI-ABS-LOW**	Gupta, Srianand
Pulsar Scintillometry at very low frequencies	**SCINT-LOW**	Kirsten (core), Simard, Main, et al.
AGN Physics at very low frequencies in COSMOS	**AGN-LOW**	Morabito
	Updated VLBI science cases with SKA1-MID telescope	
Parallax measurement of Southern Hemisphere Pulsars	**PSR-ASTR-MID**	Deller (core), Pulsar SWG
Galactic Structure using maser parallax measurements	**GAL-METH**	Ellingsen (associate), Brunthaler, van Langevelde, Imai
Adding high angular resolution to SKA surveys through wide-field-VLBI technique	**WIDEF**	Giroletti (core), Paragi, Savolainen, et al.

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Young Stellar Cluster Deep Field	**YSCLUST-MID**	Hoare (CoL), Cradle of Life Team
Exploration of the dynamics of the Galactic Bulge using OH maser parallax measurements	**GAL-OH**	Imai (core), Orosz, Burns, et al.
Resolving (ultra-)relativistic outflows with SKA-VLBI (GW-EM counterparts, Gamma-ray Bursts, Supernovae, Tidal Disruption Events, X-ray binaries etc.)	**TRANS**	Paragi (previous co-chair, core), van der Horst, Pérez-Torres, An
New VLBI science cases with SKA1-MID telescope		
A Deep Multi-Frequency VLBI Polarimetric Survey of a Big AGN Sample	**AGN-SUR**	Agudo (core), Paragi, Garrett, et al.
Chasing Merged and Merging Supermassive Black Holes	**BSMBH**	Anton, Browne, Skipper, et al.
Inhomogeneous supernovae at low frequencies (MID)	**SNe-MID**	Chandra, Bjornsson, Perez-Torres, et al.
Massive densification of the radio reference frame with SKA-VLBI: searching for Gaia counterparts	**GLOB-ASTR**	Charlot (associate), Garcia-Miro, An, et al.
High precision astrometry of continuum sources in star forming regions	**CONT-ASTR**	Dzib, Brunthaler (associate), Ortiz, Loinard
Radio emission from massive exoplanets as a powerful tool to study their properties and evolution	**EXOPL-MID**	Gawronski, Katarzyński
Pulsar Scintillometry with SKA1-MID	**SCINT-MID**	Kirsten (core), Simard, Main, et al
Testing models for galaxy formation and dark matter, and investigating the high redshift Universe with strong gravitational lensing (VLBI)	**SGRAVL**	McKean (associate), Deane, Fassnacht, et al.
Intermediate-mass black holes	**IMBH**	Mezcua (core), Argo
Studies of Ultraluminous X-ray sources -ULXs- in the local Universe	**ULX**	Middleton, Miller-Jones, David Williams, et al.
Characterising feeding and feedback in high-z radio AGN using HI absorption with SKA1-MID	**HI-ABS-MID**	Morganti (associate), Schulz, Oosterloo, et al.
Fast Radio Bursts and their hosts with SKA-VLBI	**FRB**	Paragi (core), Hessels, Marcote, et al.

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Extremely high-redshift AGN with SKA-VLBI	**HIGHz-AGN**	Perger, Frey (associate), Gabányi, et al.
SKA-Mid Ultra-Precise Astrometry to the LMC and SMC	**MC-METH**	Rioja (core), Dodson (core), Honma, Imai
Triggered VLBI of Superflares on Low-Mass Stars	**FLARES**	Villadsen
Radio and Gaia reference frames tie with radio stars	**RADIOS**	Zhang, Xu
New VLBI science case for both telescopes		
Multi-View astrometry with SKA-VLBI	**M-VIEW**	Rioja (core), Dodson (core)

Table 1. SKA-VLBI Science Cases

5.1 Scientific topics covered

The 29+1 use cases cover a very broad range of science, with quite balanced distribution. If we look from the point of view of types of targets to be observed, about one third (10) consider active galactic nuclei (AGN), one third stars or stellar systems (10), and the last third either stellar end products (neutron stars, pulsars, stellar black holes, supernova remnants - 8) or planetary systems (2). This is in line with current trends in VLBI [RD9].

If we categorize the use cases by the type of observation, a third of them requires **high precision astrometry**, eight of which is relative astrometry and two are global astrometry using quasars and radio stars. Stellar astrometry is currently a hot topic because the first two data releases were published from Gaia, and optical astrometry is approaching the precision one can do with VLBI - but there are obvious limitations to both techniques, therefore they are highly complementary. The pulsar parallax use case serves one of the highest priority science objectives of the SKA: detecting low-frequency gravitational waves and probe General Relativity theory with pulsars.

Several of the stellar astrometry projects propose to observe various transitions of masers, i.e. require **spectral line observations** rather than continuum. There are two cases to observe redshifted HI absorption in the foreground of AGN. The science case for MID will address the feeding and feedback of AGN at "high redshifts" ($1<z<3$). The science case for LOW will address active galaxies at a redshift $z>3$.

There are five science cases that require **time-critical observations** from the SKA: one on extragalactic and galactic synchrotron transients (most notably electromagnetic counterparts to sources of gravitational waves and many more), one on very short timescale transients (~millisecond, fast radio bursts), one on young stellar deep fields, one on ULXs, and one on stellar super flares from M-dwarf stars that would help us to understand the habitability of planets around low-mass stars.

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There is one case with the main objective of doing **polarimetry studies** of AGN. Some other cases do mention polarimetry (e.g. young stellar deep fields), and actually several require full-Stokes products from the SKA correlator but did not provide detailed justification. This may deserve future attention (and work), considering the unique capabilities of a SKA-VLBI array to calibrate the VLBI polarization products, and especially the available broad frequency range which will be ideal for rotation measure studies.

We particularly welcome two use cases designed to study exo-planetary systems (one for SKA1-LOW, one for SKA1-MID). There have been attempts to detect planets around stars with VLBI before, but so far without success. Apparently, the community is very positive about the future prospects using very sensitive SKA-VLBI observations. Another very interesting case that will hugely benefit from the great sensitivity of the SKA are the proposed scintillation studies in pulsars (for both LOW and MID). This will allow “imaging” their emitting regions with a stunning spatial resolution of a few km.

It has to be noted that out of the 30 use cases about a third are led by scientists who are not currently members of the SKA VLBI Science Working Group. This shows the potential to get astronomers working outside of the field of VLBI involved in future SKA-VLBI KSPs, broadening our community.

5.2 Observing strategy

All of the use cases here intend to use the multi-beam capability of the SKA. In fact, the high precision astrometry provided by this capability have been the main driver behind putting together the 8 astrometry use cases. The number of beams requested range from 2 to 16 (see Fig. 8; higher numbers are not possible unless significant trade-off is made between number of beams and observing bandwidth, i.e. sensitivity). The high number of beams will affect a SKA-VLBI array operationally in several ways. For one thing, all the data will have to be streamed (some cases in real-time during the observations) to the external VLBI correlator centre from the SKA1 telescopes. The aggregate bit rates implied by these use cases range from 5 Gbit/s to 80 Gbit/s (see Fig. 9 for a distribution). Secondly, introducing up to 10 beams or more from SKA1-MID will mean that all these beams will have to be correlated with the rest of the telescopes separately in the external VLBI correlator, each with different field of views (FoV). This means that the processing load on the VLBI correlator will increase by more than an order of magnitude. In addition, the observing bandwidth in SKA-VLBI is expected to reach up to 1 GHz at least (8 Gbit/s data rate per beam), which is a factor of 4-8 higher than the usual 1-2 Gbit/s that is operational today. Therefore, VLBI processing centres will have to find a solution well in advance to be able to handle these data at the correlator.

Considering the VLBI network that supports observations together with SKA1-MID at high frequencies (Band 3 and higher), the antennas should be equipped with broadband receivers, compatible with the SKA1 bandwidths. The BRAND-EVN project will have its first prototype

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receiver (1.5-15.5 GHz) ready by 2020 for prime-focus EVN antennas. On the other hand, at low frequencies (Band 1 and 2) the largest telescopes of the supporting VLBI array might be required to be equipped with phased array feed (PAF) receivers to match the FoV of the SKA antennas.

5.2.1 Telescope time requested and observing frequency bands

The total number of observing hours required is very similar for both SKA1 telescopes, with a total of 31,690 hrs for LOW (7 projects) and 32,540.5 hrs for MID (22 projects). These numbers are just indicative as the science cases are not rigorous proposals, but they are equivalent to almost 4 years of Key Science and PI Projects devoted to VLBI science with each of the SKA1 telescopes. Previously published VLBI science cases only requested 8,550 hrs [RD4]. Tables 2-4 show the time required per observing band and project.

Most of LOW projects observe the whole frequency band that for VLBI beams is restricted to 256 MHz (4x64 MHz subbands). Of the 22 SKA1-MID proposals roughly half requests frequencies below 2 GHz (Band 1, Band 2) and the other half requires frequencies above 5 GHz (Band 5, Band 6) (see Fig. 4), with 8 projects requesting dual-band observations.

Band 5 receiver split into Band 5a and 5b affects to several projects that need broadband observations, such as the Scintillation project and all AGN related projects, including one Global astrometry case. A Band 6 extension would benefit at least 4 projects.

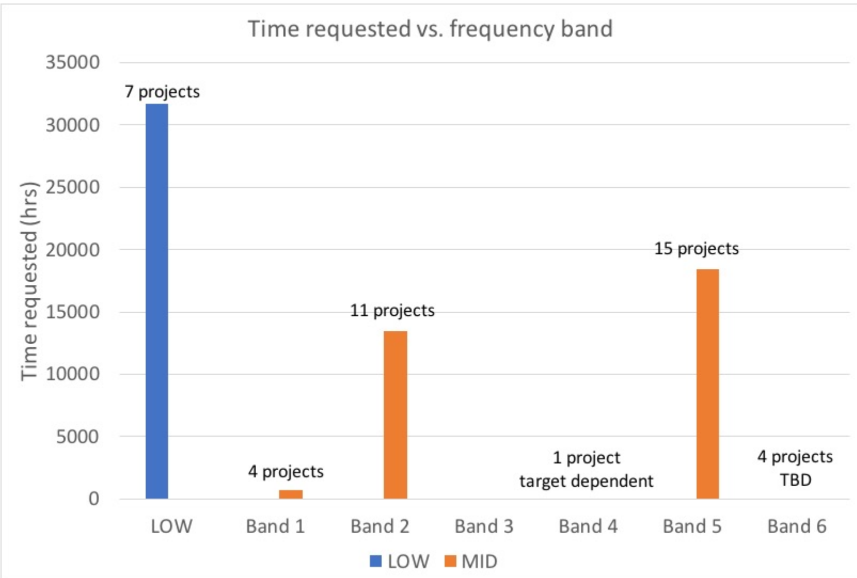

Figure 4. Telescope time requested per frequency band

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Science case code	Time Required (hrs)	SKA1-LOW Band	PI
YSO-LOW	400	whole	Ainsworth
PSR-ASTR-LOW	16,000	whole	Dodson
EXOPL-ASTR-LOW	4,800	whole	Guirado
HI-ABS-LOW	200	whole	Gupta
SCINT-LOW	200	whole	Kirsten
AGN-LOW	10,000	whole	Morabito
SNe-LOW	90	150 MHz (200-350 MHz)	Chandra

Table 2. Telescope time requested for SKA1-LOW (new cases)

Science case code	Time Required (hrs)	SKA1-MID Band	PI
PSR-ASTR-MID	800	Band 2	Deller
GAL-METH	1,500	Band 5	Ellingsen
WIDEF	2,500	Band 2	Giroletti
YSCLUST-MID	1,000	Band 5+	Hoare
GAL-OH	2,000	Band 2	Imai
TRANS	target/750	Band [4], 5	Paragi

Table 3. Telescope time requested for SKA1-MID (updated cases)

Science case code	Time Required (hrs)	SKA1-MID Band	PI
AGNSUR	750	Band 5+	Agudo
BSMBH	1,000	Band 5	Anton
CONT-ASTR	100	Band 5	Dzib
GLOB-ASTR	5,000	Band 5	Charlot
HIGHz-AGN	1,000/1,000	Band 2, 5	Perger
EXOPL-MID	200/200	Band 1, 2	Gawroński
SCINT-MID	1,000 simult.	Band 1, 2, 5	Kirsten
IMBH	4,500/1,500	Band 2, 5	Mezcua
ULX	150	Band 5	Middleton
HI-ABS-MID	100/100	Band 1, 2	Morganti
SGRAVL	1,250/750	Band 2, 5	McKean
FRB	750	Band 2	Paragi
MC-METH	4,000	Band 5	Rioja
FLARES	100	Band 5	Villadsen
RADIOS	500	Band 5	Zhang
SNe-MID	30/10.5	Band 1, 2	Chandra

Table 4. Telescope time requested for SKA1-MID (new cases)

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5.2.2 Operational mode

The projects presented (Fig. 5) are roughly divided between just one epoch observations (for e.g. surveys) or several epochs (for e.g. follow-ups). Many need a fixed schedule with certain observing cadence, mainly the astrometric projects that measure the parallax signature and the follow-up projects that characterize variability. Five projects are time critical and will be either triggered internally or externally to SKA1 by VOEvents, or will themselves produce triggers for transients' follow-up.
As previously noted, 8 projects have requested dual-band observations, but 3 of them would need to be observed in an (almost)-simultaneous way, using different observing methods, such as definition of different subarrays, frequency agility or very close in time observing sessions. There are also 2 cases (SCINT and SNe) that would benefit from simultaneous observations with both SKA1 telescopes.

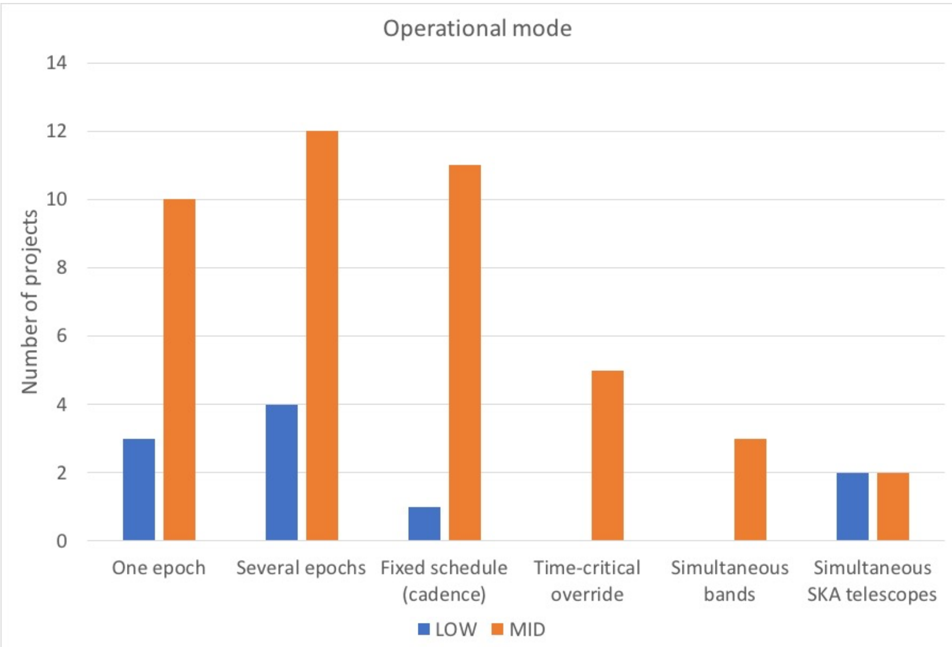

Figure 5. Operational mode

5.2.3 Science data products

All science cases require SKA1 local interferometer imaging data products in addition to the VLBI tied-array beams (Fig. 6). The main purpose is the enhancement of the calibration of the VLBI data products, but these also allow complementary science studies of the targets.

Although VLBI beams will be mostly formed from a core subarray, most of the projects will use the interferometer products from the whole array to provide local interferometric images. It will be evaluated at a later stage whether this is a justified scientific requirement for all the

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projects. If imaging from the same core subarray is sufficient (to calibrate the VLBI data products), then some resources are freed up in CSP.

A number of projects will also require polarisation imaging products for studies of the magnetic field structure and interaction of the target with its environment. The spectral line projects such as the observations of maser lines and HI absorption will also use a zoom window for high frequency resolution maps. The projects that will observe pulsars will benefit from using a pulsar timing beam to refine their ephemerides. Transient projects may use pulsar search beams and download the transient buffer if required.

Many of these science cases (about 10) can be potentially observed commensally with other projects, such us the continuum and spectral line surveys, and the global astrometry cases (GLOB-ASTR and RADIOS).

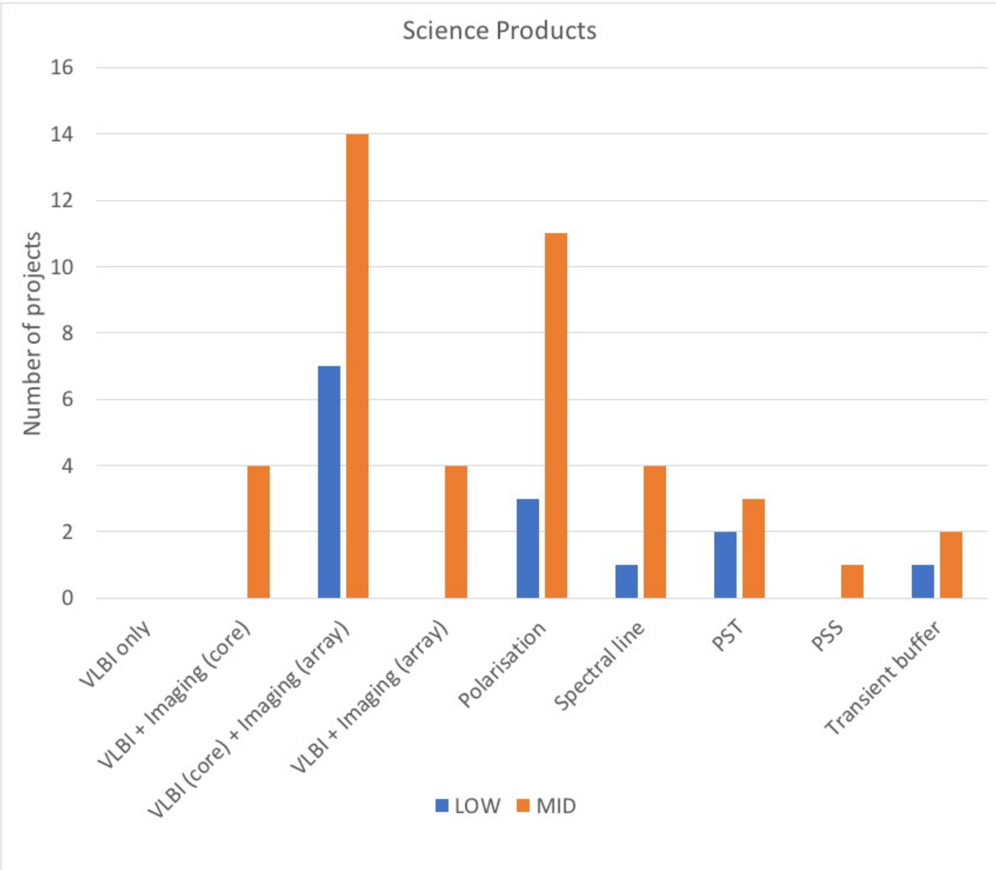

Figure 6. Science data products

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5.2.4 Number of subarrays and size

Most of the science cases use one subarray formed by the SKA1 core to produce the VLBI tied-array beams. Operationally this is achieved considering the whole array but giving zero weights to the antennas or stations outside of a certain radius.

For dual-band simultaneous observations there is one case (SCINT-MID) that will use 3 subarrays with same resolution and sensitivity, and possibly another 5 cases could use 2 subarrays (GLOB-ASTR, SNe-MID, AGNSUR, HIGHz-AGN, EXOPL-MID).

The subarray size is a trade-off between sensitivity and field of view in the VLBI beams but will also depend on the SKA1 beamforming stability (Fig. 7). Astrometry projects in general phase-up the whole array (for LOW up to 20 km radius limitation) unless accuracy in the a-priori coordinates is not good enough. The remaining projects phase up just the core, mostly the inner 4 km radius with 70-80% of total sensitivity depending on the observing band. One project (WIDEF) will use 2 different subarray radii (0.5 and 2 km) for survey and targeted observing modes and 4 projects will benefit from selectable subarray size depending on the target characteristics.

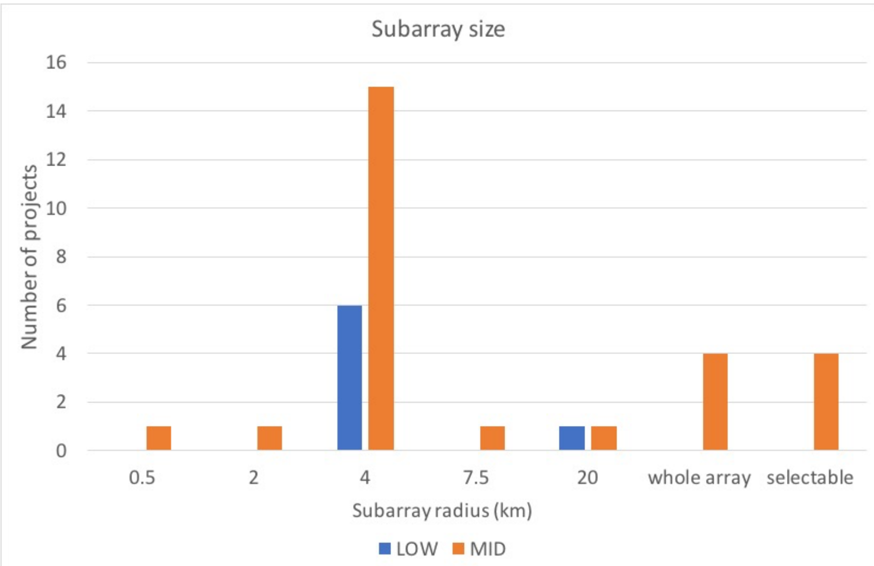

Figure 7. Subarray size

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5.2.5 Number of VLBI beams

Multiple VLBI beams are required for all the projects, from 2 beams up to 16 (see Fig. 8). Many projects need them for phase referencing techniques and high precision astrometry, increasing the number of beams for more precise position determinations. The rest of the projects need as many sensitive VLBI beams as possible to observe efficiently a high density of targets within the FoV. The number of beams is limited by both SKA1 correlators resources. If this limitation could be alleviated, at least 6 projects could use more than 16 beams if available.

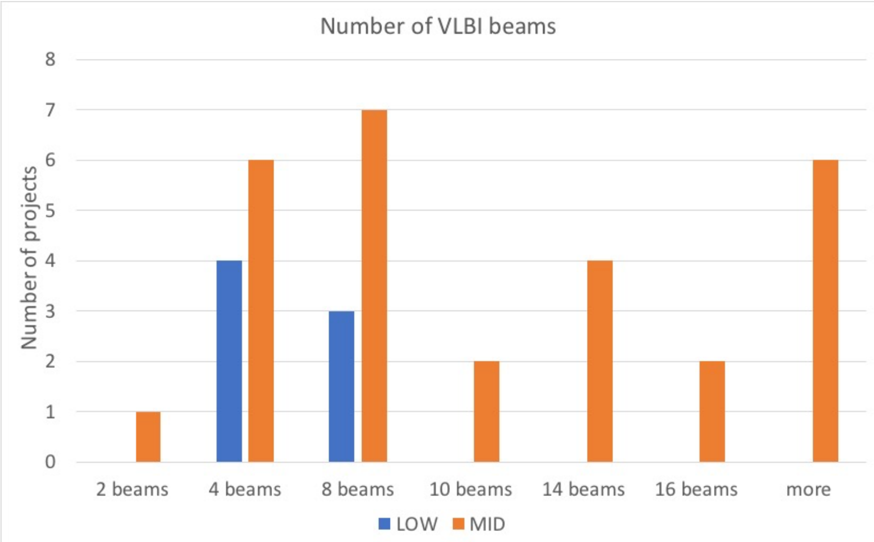

Figure 8. Number of VLBI beams

5.2.6 Aggregate data rates

Multiple VLBI beams increase the aggregate data rate that needs to be transferred to the external VLBI correlator. Figure 9 shows the various data rates for the different configurations and projects, with higher data rates demand for SKA1-MID with larger observing bandwidths. Real-time transfer and correlation (e-VLBI mode) is necessary for some of the projects (4) for fast turnaround of the results. This mode benefits all the other projects for real-time fringes verification and problem finding and alleviates the buffer size required at the VLBI terminal, located at the Science Processing Centre in Perth or Cape Town.

The solutions to be presented for LOW and MID telescopes are quite different; for example, a limitation to 20 Gbps data rate from the SKA1 telescope, allows all LOW-VLBI science but forbids most of MID-VLBI science.

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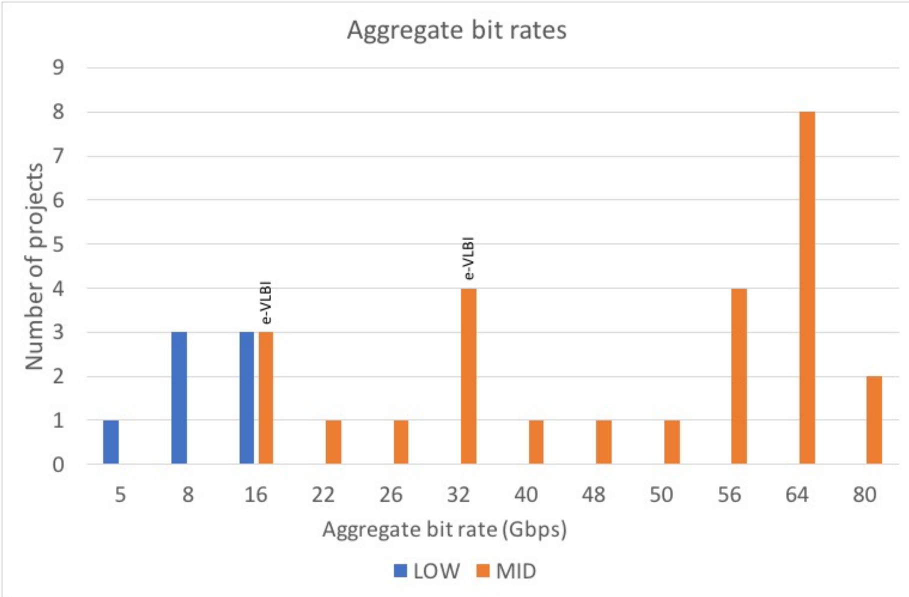

Figure 9. Aggregate bit rates

5.2.7 Central Signal Processor configuration

This section focuses on the configuration of the SKA1-LOW and MID Central Signal Processor element, with respect to the correlation and beamforming functions [RD2].

SKA1-LOW can process simultaneously all observing modes for each subarray, with a maximum of 16 subarrays. About half of the projects only need 4 VLBI beams but the rest need to use multi-view capability for precise astrometry with at least 8 VLBI beams. All projects need VLBI beams simultaneously with Imaging from the whole SKA1-LOW interferometer, with full bandwidth (256 MHz maximum bandwidth for VLBI beams) unless specified. Few specific projects require polarisation products, zoom windows for spectral line, pulsar beams or transient buffer data. Refer to Table 5 for details.

Science case code	**VLBI # x b/w**	**Imaging**	**Spectral Line**	**PST**	**Transient buffer**
YSO-LOW	4x256 MHz	256 MHz Pol			
PSR-ASTR-LOW	8x256 MHz	256 MHz		x	x
EXOPL-ASTR-LOW	8x256 MHz	256 MHz Pol			
HI-ABS-LOW	4x256 MHz	256 MHz	x		
SCINT-LOW	8x256 MHz	256 MHz		x	
AGN-LOW	4x256 MHz	256 MHz Pol			
SNe-LOW	4x150 MHz	150 MHz			

Table 5. CSP configuration for SKA1-LOW cases

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SKA1-MID is limited by processing resources at the correlator (up to 26 processing units FSPs -Frequency Slice Processors- available) and cannot process simultaneously all observing modes with full bandwidth for each subarray. There are 2 projects impacted by this limitation (YSCLUST-MID and SGRAVL) as they requested full Band 5 imaging plus VLBI beams. A compromise had to be made to the imaging bandwidth to accommodate few VLBI beams, but they would need more. Other projects would like to have more VLBI beams available as well to improve observing efficiency, but again resources do not permit, e.g. BSMBH, HIGHz-AGN, GAL-METH, WIDEF, CONT-ASTR and IMBH.

Not many projects indicated the use of the VLBI visibilities that are generated from the same subarray that produces the VLBI beams and come for free without consuming additional correlator resources. In general, most of the projects require imaging products from the whole SKA1-MID array, using normal visibilities, and they assign remaining processing resources to generate VLBI beams, as many as possible. About half of the projects require polarisation products. A few specific projects require zoom windows for spectral line, pulsar beams or transient buffer data. Refer to Tables 6 and 7 for details.

Science case code	VLBI # x b/w	Imaging VLBI visibilities	Normal Imaging	Spectral Line	PST	PSS	Transient buffer
PSR-ASTR-MID	8x500 MHz (12 FPS)	500 MHz			1x500 MHz (3 FPS)		
GAL-METH	14x500 MHz (21 FPS)		500 MHz (3 FPS)	2.3 MHz (1 FPS)			
WIDEF	14x500 MHz (21 FPS)		500 MHz Pol (3 FPS)				
YSCLUST-MID	4x400 MHz (4 FPS)		4.4 GHz (22 FPS)				
GAL-OH	14x500 MHz (21 FPS)		500 MHz Pol (3 FPS)	3.1 MHz (1 FPS)			
TRANS	8x1 GHz (20 FPS)		1 GHz Pol (5 FPS)				x

Table 6. CSP configuration for SKA1-MID updated cases

Science case code	VLBI # x b/w	Imaging VLBI visibilities	Normal Imaging	Spectral Line	PST	PST	Transient buffer
AGNSUR	10x500 MHz (15 FPS)		2 GHz Pol (10 FPS)				
BSMBH	6x1 GHz (15 FPS)		2 GHz Pol (10 FPS)				
CONT-ASTR	16x500 MHz (24 FPS)	500 MHz					
GLOB-ASTR	2x1 GHz (5 FPS)	1 GHz					
HIGHz-AGN	8x1 GHz (20 FPS)		1 GHz Pol (5 FPS)				

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EXOPL-MID	14x500 MHz (21 FPS)		500MHzPol (3 FPS)				
SCINT-MID	4x500 MHz (6 FPS)		500 MHz (3 FPS)		1x500 MHz (3 FPS)		
IMBH	10x1 GHz (25 FPS)	1 GHz					
ULX	4x1 GHz (10 FPS)		1 GHz Pol (5 FPS)				
HI-ABS-MID	4x500 MHz (6 FPS)		500MHzPol (3 FPS)	3.1 MHz (1 FPS)			
SGRAVL	8x1 GHz (20 FPS)		1 GHz (5 FPS)				
FRB	4x500 MHz (6 FPS)		500MHzPol (3 FPS)		1x500MHz (3 FPS)	1500x300MHz (8 FPS)	X
MC-METH	8x1 GHz (20 FPS)	1 GHz		2 MHz (1 FPS)			
FLARES	4x1 GHz (10 FPS)		1 GHz Pol (5 FPS)				
RADIOS	8x1 GHz (20 FPS)	1 GHz					
SNe-MID	4x1 GHz (10 FPS)		1 GHz (5 FPS)				

Table 7. CSP configuration for SKA1-MID new cases

The following figures are examples of different CSP MID correlator configurations, for projects that assign most of the resources to the VLBI beams (e.g. GAL-OH, Figure 10), or need to assign most of resources to Imaging due to the large bandwidth (e.g. YSCLUST-MID, Figure 11), or use subarrays to observe simultaneously different frequency bands, using the same FSPs to process the different subarrays (e.g. SCINT-MID, Figure 12).

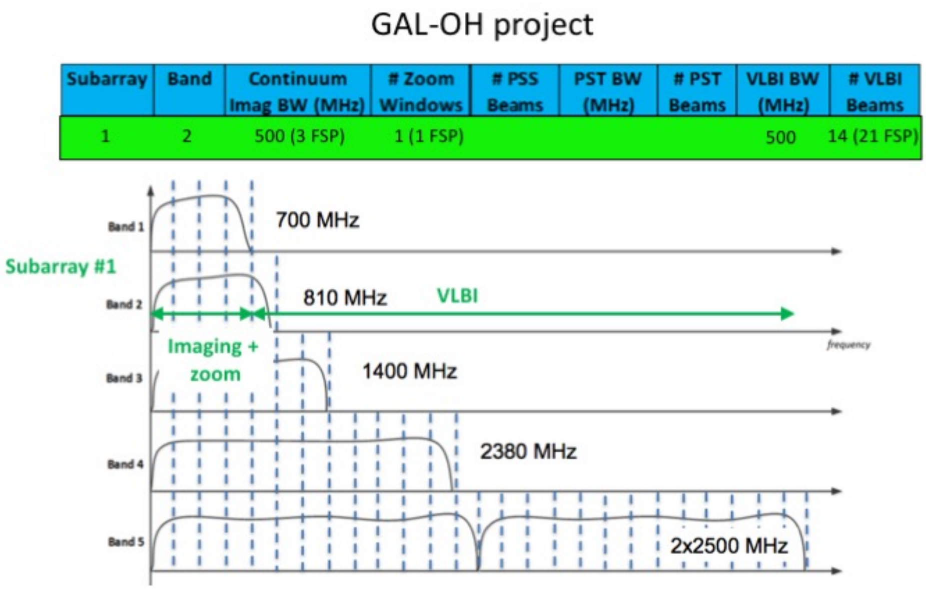

Figure 10. CSP resources for GAL-OH project: most of resources assigned to VLBI beams

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YSCLUST-MID project

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	4.4 GHz (22 FSPs)					400	4 (4 FSPs)

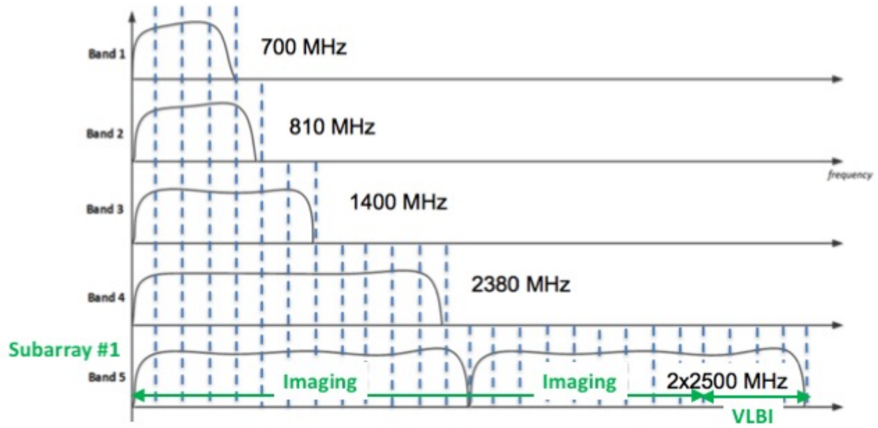

Figure 11. CSP resources for YSCLUST-MID project: most of resources assigned to Imaging

SCINT-MID project

Subarray	Band	Continuum Imag BW (MHz)	# Zoom Windows	# PSS Beams	PST BW (MHz)	# PST Beams	VLBI BW (MHz)	# VLBI Beams
1	5	500 (3 FSPs)			500 (3 FSPs)	1	500	4 (6 FSPs)
2	2	500 (3 FSPs)			500 (3 FSPs)	1	500	4 (6 FSPs)
3	1	500 (3 FSPs)			500 (3 FSPs)	1	500	4 (6 FSPs)

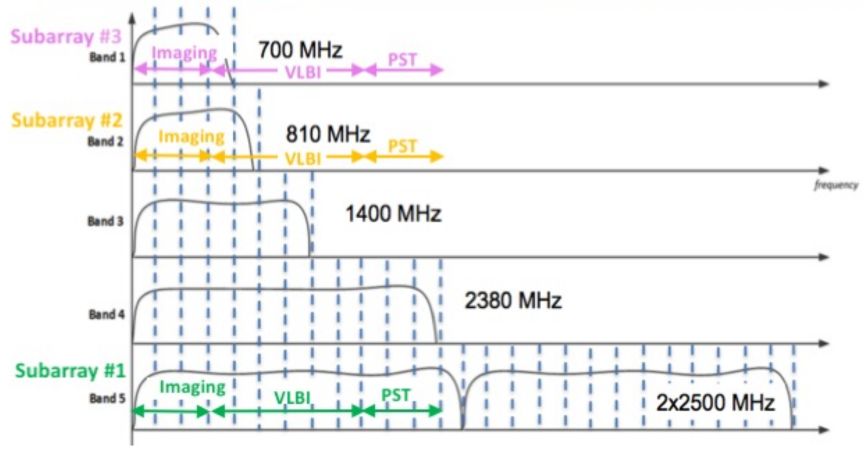

Figure 12. CSP resources for SCINT-MID project: process of 3 subarrays using the same resources

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5.3 Comments and issues

The science case form includes a section for issues to be determined or resolved for each of the projects. In general, all the projects need established policies on how the SKA1 telescopes will participate in VLBI observations, some projects also need policies for ToO, triggers and overrides, with fast response from the VLBI network and the SKA1 telescopes.

For SKA1-LOW the main issue is the availability of an appropriate VLBI network with common visibility and frequencies, but planned and sensitive Asian antennas and possibly space antennas should provide an adequate network on SKA1's timescales. This applies also to Band 1 for SKA1-MID. Another issue is the number of VLBI beams available (only 4): for precise astrometry using Multi-view, at least 8 would be needed.

For SKA1-MID one main issue is the insufficient processing resources to provide full Band 5 imaging and VLBI beams simultaneously. This has a large impact on plans to piggy-back VLBI observations on SKA continuum surveys in Band 5. The limited number of sensitive VLBI beams will have to be overcome by fast reconfiguration and calibration of the subarrays and of the available beams, to cover the required FoV, with regular updates to the target list (daily and even in real-time). Accurate calibration of the VLBI beams with appropriate metadata will be needed, to asses beamforming performance. On the other hand, solutions like automatic gain control with discrete voltage level jumps may hinder fast transient search. Additionally, beam subbands' largest bandwidth is not the most convenient choice to be fully compatible with the new generation of VLBI backends (200 MHz vs. 256 MHz).

Several issues apply only to particular MID projects, such as the need to perform Multi-frequency Rotation Measure (RM) synthesis and produce I, Q, U, V and RM images cubes (AGNSUR). The calibration of ionospheric and instrumental effects using only Band 5a or 5b and different subarrays would need to be demonstrated (GLOB-ASTR). Some projects may use raw visibilities and voltages for post-observation beamforming in e.g. the SKA science regional centres (SGRAVL). For FRB observations there is a need for coordination between CSP and the external VLBI correlator to apply same de-dispersion parameters. Lastly, for the Multi-View approach, ionospheric residuals have been shown to allow µas accuracy, but the same needs to be verified for the troposphere and the calibrators stability needs to be tested at the sub-µas level (M-VIEW).

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6 Conclusions

The portfolio of science cases presented in this deliverable represents a broad sample of the transformational science that SKA-VLBI will realised. These are merely examples that will eventually evolve into mature proposals for SKA Key Science and PI Projects, to be discussed at the future SKA-VLBI Key Science Projects and Operations workshop, 14-17 October 2019 (https://indico.skatelescope.org/event/539/).

This report outlines the major outcomes derived from the study of the science cases, with respect to the capabilities and requirements needed, observing strategies, science data products, etc. It also shows the observing limitations imposed by the SKA1 design and the issues that need to be determined or resolved for some cases.

References

[RD1] Design Baseline Description, SKA-TEL-SKO-0000002, Rev 3
[RD2] SKA1 CSP Element Architectural Design Document, SKA-TEL-CSP-0000014, Rev 4
[RD3] SKA Phase 1 System Requirements Specification, SKA-TEL-SKO-0000008, Rev 11
[RD4] SKA1 Scientific Use Cases, SKA-TEL-SKO-0000015, Rev 3
[RD5] Garcia-Miro et al., Proceedings of 14th EVN Symposium, October 2018, Granada, Spain. Online at https://arxiv.org/abs/1903.08627
[RD6] Paragi, Chrysostomou, Garcia-Miro, Proceedings of 14th EVN Symposium, October 2018, Granada, Spain. Online at https://arxiv.org/abs/1901.10361
[RD7] Anticipated SKA1 Science Performance, SKA-TEL-SKO-0000818, Rev 1
[RD8] EVN status tables. Online at http://old.evlbi.org/user_guide/EVNstatus.txt
[RD9] Paragi et al., Proceedings of Advancing Astrophysics with the Square Kilometre Array (AASKA14). 9 -13 June, 2014. Giardini Naxos, Italy. Online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215, id.143

ANNEXES

ANNEX 1: SKA-VLBI Science Cases forms

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

1.1 M-VIEW: Multi-View astrometry with SKA-VLBI

PROJECT DETAILS	
Title	**Multi-View astrometry with SKA-VLBI**
Principal Investigator	**Maria Rioja and Richard Dodson**
Co-Authors	
Time Request	

FACILITY		Preconditions
X	SKA1-LOW	VLBI mode (multiple tied array beams)
X	SKA1-MID	VLBI mode (multiple tied array beams)

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	
X	SKA1-MID Band 1	
X	SKA1-MID Band 2	
X	SKA1-MID Band 3	
X	SKA1-MID Band 4	
X	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	Schedule in collaboration with Global VLBI community
	Sub-arrays required	

COMMENTS ON OBSERVING STRATEGY
We focus on the astrometry requirements for a number of accepted science cases, as these details were not discussed.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or CORRELATOR ( )*			
X	XX		Stokes I
X	YY		Stokes Q
	XY		Stokes U
	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
This case provides missing details for projects PSR-ASTR-LOW (1.4), EXOPL-ASTR-LOW (1.5), SCINT-LOW (1.7) and MC-METH (1.28), or any other VLBI project that does not solely depend on self-calibration,

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Astrometry at Low Frequencies has a requirement to achieve 10uas accuracy. SKA-VLBI has the thermal sensitivity to achieve 1uas. If multiple tied array beams are provided by the SKA-VLBI solutions can be interpolated to the line of sight to give zero systematic errors, which should allow the thermal limits to be reached.
We estimate the number of required beams and the maximum baseline length that could be included, given the directional dependent corrections required.
For SKA the most useful mode will be full-bandwidth multiple tied-array beams with the FoV of the partner observatories (20m at L-band ~0.5 deg; Dodson 2018, Rioja 2019). In this domain the phase surface over the MWA provides a guide (Rioja 2018).

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (VLBI)
Number of targets		
Positions of targets		
Rapidly changing sky position? (e.g. comet, planet)	X	YES [details: Spacecraft Tracking mode]
		NO
Time Critical?		YES [details: ……………………………………….]
	X	NO (but in coordination with other observatories)
Integration time per target (hrs)		
Average peak flux density (Jy or Jy per beam)		
Range of peak flux densities (Jy or Jy per beam)		
Expected polarised flux density (expressed as % of total)		

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	
Total Bandwidth (MHz)	
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	
Temporal resolution (in seconds)	

NON-IMAGING SPECIFIC CONSIDERATIONS	
Required angular resolution of a tied array beam (arcmin)	Highest sensitivity possible, so small as possible.
Maximum baseline required (km)	Suggest aim at core only
Primary beam size (sq degrees)	N/A
Number of output channels	Nyquist
Output bandwidth (minimum and maximum frequency - MHz)	
Required rms (Jy) (if polarisation products required define for each)	
Dynamic range (if polarisation products required	

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define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a ‘support image’ in the case of VLBI observations)		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of output channels		
Output bandwidth (minimum and maximum frequency - MHz)		
Required rms (Jy per beam) (if polarisation products required define for each)		
Dynamic range within image (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth)		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (VLBI)		
Required angular resolution (arcmin) (single value or range)		
Mapped image size (degrees)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5% (This will be the SEFD estimate in the analysis)
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	
Data products	Dual polarisation voltage data for cross correlation with other observatories, from multiple simultaneous tied array beams.
Description of pipeline	SKA must provide a calibration solution for each beam. Over 0.5 deg, for SKA-Low, these will be different.
Quality assessment plan & cadence	
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.)	

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Multiple tied array VLBI beams can provide interpolated astrometric solutions for the target line of sight. The quality of using planar solutions has been demonstrated (Rioja 2017), providing the *initial* requirement of **3 calibrator and one target beams** (ie 4 beams). We have done a preliminary study of the level to which planar solutions are acceptable (Dodson 2018). We find, from MWA data, that within a ~0.5deg FoV, planar solutions are good for 90% of the directions for MWA baselines <6km. The remaining 10% can be approximated by a plane with losses of ~10%. Because of the latter point we would recommend more than the minimum, i.e. **6 beams (5 cals + 1 target)** to allow for the solution for curvature in the dTEC surface. Studies to provide robust statistics of the MWA solutions are required to improve this estimate. To achieve the potential thermal accuracies calibrator behaviour has to be addressed. For that we need more than the minimum number of beams. An additional two (1 per dimension) will allow these checks. Thus we would recommend **8 beams (7 cals + 1 target)** for 1uas astrometry. Calibration of multiple tied array beams requires direction dependent solutions. The dTEC surface over the core of the array would provide these solutions. Therefore the **real time DD solutions will need to be solved for, fitted, and applied** to the tied-array beams. Estimates of the area which can be summed together requires characterisation of the dTEC surfaces at SKA sites. From the MWA observations we find dTEC differences of 20mTEC over 6km as typical. These data suggest that a low order polynomial fit to the dTEC surface will be sufficient to provide the DD solutions for the tied array beams. The studies to provide robust statistics of the MWA solutions will improve this supposition.

REFERENCES
Rioja et al. 2017; MultiView High Precision VLBI Astrometry at Low Frequencies, 2017AJ....153..105R Rioja et al. 2018 LEAP: an innovative DD ionospheric calibration scheme, 2018MNRAS.478.2337R Rioja et al. 2019; Astrometry Review, A&AR, in prep Dodson et al. 2018; EVN contribution, POS, in prep

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

1.2 YSO-LOW: Jets from low mass Young Stellar Objects at very low frequencies

PROJECT DETAILS	
Title	**Jets from low mass Young Stellar Objects at very low frequencies**
Principal Investigator	**Rachael Ainsworth**
Co-Authors	**Anna Scaife**
Time Request	2-4hrs per target, 400hrs in total

FACILITY		Preconditions
X	SKA1-LOW	Observations to be arranged jointly with a VLBI array.
	SKA1-MID	

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	2-4hrs per target
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
X	Normal	
X	Fixed schedule (give cadence)	every 1-2 years for individual ejections proper motion determination
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core for beamforming

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW array interferometer images, for complementary studies of the target at different angular scales and total flux density and polarization monitoring. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q

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X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Low mass young stellar objects (YSOs; ~ 1 M⊙) are best suited to study the launching and collimation mechanism of jets in detail (Anglada et al. 2018) due to their relative proximity (140pc for the nearest star forming regions; Ortiz-León et al. 2018). With a spatial resolution of ~0″.025−0″.2, SKA-VLBI will probe the jet launching region on scales down to 3–30 au, resolving the jet not only along the flow, but also potentially across – providing a new diagnostic on the jet opening angle near to the source. Multi-wavelength observations for spectral index constraints at such low frequencies will help determine physical properties of the ionised plasma (e.g. emission measure, electron density; Coughlan et al. 2017). Low frequency observations also provide a unique tool for probing non-thermal synchrotron emission (e.g. Ainsworth et al., 2014). It will allow us to study the dynamics of the outflows and to perform detailed investigations of their interaction with the external medium. Measurements of polarisation will give reliable estimates of the magnetic field distribution in the outflows, enabling investigations of the role it plays on extended scales (Ray, 2010).

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (VLBI)
Number of targets		As many from Anglada et al. 2018 that are observable with SKA1-LOW, about 100 targets.
Positions of targets		Individual targets within a single FoV of individual SKA1-LOW station
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO every 1-2 years for individual ejections proper motion determination
Integration time per target (hrs)		~10 minutes per target will get a sufficient detection (assuming 0.2 mJy/beam level for 60sec integration, full b/w, 1-sigma), but suggest a few hours (2-4h) to half a synthesis for UV coverage for imaging.
Average peak flux density (Jy or Jy per beam)		1 mJy
Range of peak flux densities (Jy or Jy per beam)		0.1-1 mJy
Expected polarised flux density (expressed as % of total)		A few %

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Frequencies to be determined depending on the VLBI array capabilities, e.g. 149 MHz, 200 MHz, 323 MHz
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Temporal resolution (in seconds)	Standard Nyquist sampling

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OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Spectral resolution (kHz)	Standard for Low correlator
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-LOW station	
Required angular resolution of a tied array beam (arcmin)	178/25.5 arcsec (50/350MHz, 600/86cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min	
Primary beam size (FWHM, arcmin)	40m stations 10deg/1.4deg (50/350MHz, 600/86cm)	
Total bandwidth for each tied array beam	256 MHz (equivalent to 2 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	4	
Output bandwidth (minimum and maximum frequency - MHz)	64 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a ‘support image’ in the case of VLBI observations, for SKA1-LOW local interferometer data)	
Required angular resolution (arcmin) (single value or range)	Several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies
Maximum baseline required (km)	Full array
Mapped image size (degrees)	Standard FoV
Required pixel resolution (arcseconds)	standard
Number of output channels	standard
Output bandwidth (minimum and maximum frequency - MHz)	256 MHz bandwidth (same as VLBI beams)

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Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-LOW continuum sensitivities (from 10 to 160 μJy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	25 mas to 0.2 arcsec depending on observing frequency	
Mapped image size (degrees)	Up to 25x25 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min	
Dynamic range within image (if polarisation products required define for each)	>50 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-LOW will participate in VLBI observations.

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Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-LOW interferometer images from the full array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec level, for different epochs.
Description of pipeline	Standard imaging pipeline for SKA1-LOW, Standard VLBI pipelines for SKA-VLBI Low frequency data (equivalent to LOFAR International Baselines Pipeline)
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	Provide SDP products in a timely manner. VLBI beam voltages to be sent to the external correlator within 2 weeks from observation date.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
VLBI Low frequency array is currently in development. Fringes between MWA and uGMRT were demonstrated recently (Kirsten et al. 2016). Few telescopes will have low frequency capability (e.g. GMRT, FAST, Miyun, Past and Tianlai, etc.), with limited uv coverage, image reconstruction algorithms for low frequencies will need to be improved.

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

1.3 SNe-LOW: Inhomogeneous Supernovae studies at low frequencies

PROJECT DETAILS	
Title	**Inhomogeneous Supernovae studies at low frequencies**
Principal Investigator	**Poonam Chandra**
Co-Authors	**Claes-Ingvar Bjornsson, Miguel Perez-Torres, A. J. Nayana, Peter Lundqvist**
Time Request	130.5 hrs

FACILITY		Preconditions
X	SKA1-LOW	Observations to be arranged jointly with a VLBI array.
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	90 hrs (including 30% overhead, in 3 years)
X	SKA1-MID Band 1	30 hrs (including 30% overhead, in 3 years)
X	SKA1-MID Band 2	10.5 hrs (including 30% overhead, in 3 years)
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	We need near-simultaneous one observation with SKA-LOW (200-350 MHz subband), SKA1- MID (Band 1) and SKA1-MID (Band 2). We also need another set of near-simultaneous observation around 15 days apart with SKA1-MID (Band 1) and SKA1-MID (Band 2).
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW and SKA1-MID array interferometer images, for complementary studies of the target at different angular scales and total flux density and polarization monitoring. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. Simultaneous observations in Band 1 and 2 could be done using 2 subarrays, 1 subarray with frequency agility. VLBI array could be divided in 2 subarrays for each frequency.

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

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
In supernovae (SNe), inhomogeneous emission is caused by variations in the distribution of relativistic electrons and/or the magnetic field within the synchrotron emitting region. This results in a flatter spectral index in the optically thick part due to superposition of varying optical depths. The presence of inhomogeneities would affect several of the conclusions drawn from observations using the standard synchrotron model. The most important is the size of the source thus the derived velocity. If direct velocity estimates are available from other wavelengths, they are generally higher than deduced from radio observations of spatially unresolved SNe with inhomogeneities. This has important consequences in presence of anticipated central engine in some stripped-envelope SNe. However, it is difficult to reveal the presence of inhomogeneities in spatially unresolved sources as the spectrum in the transition region is degenerate. Spatially resolved observations are needed to break this degeneracy and deduce magnetic field and broadness of spectrum caused by inhomogeneities. If inhomogeneities are present, spatially resolved observations via SKA-VLBI will result in higher velocities. To reveal the inhomogeneities in SNe, SKA-VLBI observations, either quasi-simultaneously at two different frequencies within the transition region or at one given frequency at two different times are needed.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
		Non-imaging pointings
Number of targets	Type Ib/c core collapse supernovae within 10 Mpc. 10 targets per year.	
Positions of targets	Individual targets within a single FoV of individual SKA1-LOW station and SKA1-MID dish	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?	X	YES [details: observing twice with a gap of ~15 days around SN radio peak]
		NO
Integration time per target (hrs)	For SKA1-LOW: 0.2 mJy/beam level for 60sec integration, 1-sigma. **~ 3 hrs** For SKA1-MID: between 60microJy/beam for band 1 to 30 microJy for band 2, for 60sec integration, 1-sigma. **Band 1 (30 minutes x twice), Band 2 (10 minutes x twice)**	
Average peak flux density (Jy or Jy per beam)	200 μJy	
Range of peak flux densities (Jy or Jy per beam)	0.1 mJy - 2 mJy	
Expected polarised flux density	<1%	

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(expressed as % of total)	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW (200-350 MHz) SKA1-MID band 1 and 2 centres
Total Bandwidth (MHz)	150 MHz for LOW 700 MHz for band 1 (whole band) 810 MHz for band 2 (whole band).
Minimum and maximum frequency over the entire range of the setup (MHz)	200-350MHz 0.35-1.05 GHz 0.95-1.76 GHz
Spectral resolution (kHz)	Minimum 500 kHz (external correlator concern)
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW (200-350 MHz)
Total Bandwidth (MHz)	150 MHz for LOW 700 MHz for Band 1 (whole band) 810 MHz for Band 2 (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	200-350MHz 0.35-1.05 GHz 0.95-1.76 GHz
Spectral resolution (kHz)	Standard for Low correlator Standard for Mid correlator
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS	
Number of subarrays	1 (2 for simultaneous observations)
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-LOW station or SKA1-MID dish, at least 4 (1 target + 3 calibrators)
Required angular resolution of a tied array beam (arcmin)	178/25.5 arcsec (50/350MHz, 600/86cm and 4 km radius subarray) 9/5.4 arcsec (900/1600MHz, 30/18cm and 4 km radius subarray)
Maximum baseline required (km)	8
Required baseline sensitivity	Between SKA1-LOW VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min Between SKA1-MID VLBI beam and a 100m-class dish is ~ 70/30 microJy in 1 min for Band 1/2.
Primary beam size (FWHM, arcmin)	40m stations 10/1.4deg (50/350MHz, 600/86 cm) 15m dishes 1.3/0.8deg (900/1600MHz, 30/18 cm))
Total bandwidth for each tied array beam	For LOW 150 MHz (equivalent to 1.2 Gbps data rate for 2-bit sampling per VLBI beam) For MID 800 MHz (equivalent to 6.25 Gbps data rate for 2-bit sampling per VLBI beam)
Number of output channels	4
Output bandwidth (minimum and	64 MHz per channel for LOW

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maximum frequency - MHz)	200 MHz per channel for MID	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-LOW/MID local interferometer data)		
Required angular resolution (arcmin) (single value or range)	For LOW several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies For MID 0.2 arcsec for highest frequencies, up to 1 arcsec for the lowest frequencies	
Maximum baseline required (km)	Full LOW/MID array	
Mapped image size (degrees)	Standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	150 MHz bandwidth 700/800 MHz bandwidth for Band 1/2	
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-LOW continuum sensitivities (from 11×10^{-6} to 163×10^{-6} Jy/beam for 1h integration) Typical SKA1-MID continuum sensitivities for Band 1/2 (from 1.7×10^{-6} to 15.6×10^{-6} Jy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A	
Required angular resolution (arcmin) (single value or range)	
Maximum baseline required (km)	
Mapped image size (degrees)	
Required pixel resolution (arcseconds)	

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Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	25 mas to 0.2 arcsec depending on observing frequency for LOW ~mas for MID (depending on obs. frequency, VLBI array config., data weighting)	
Mapped image size (degrees)	Up to 5x5 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1-LOW VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min Between SKA1-MID VLBI beam and a 100m-class dish is ~ 70/30 microJy in 1 min for Band 1/2.	
Dynamic range within image (if polarisation products required define for each)	>50 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-LOW/MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-LOW/MID interferometer images from the full arrays. Final SKA-VLBI data products produced by the PI will

	be high angular resolution maps of the targets, up to sub-arcsec or mas level (depending on observing frequency).
Description of pipeline	Standard imaging pipeline for SKA1-LOW/MID, standard VLBI pipelines for SKA-VLBI data.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	No time critical, similar cadence as external correlator.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
To get practically thermal noise limited data on the primary target, having ~>1 mJy compact calibrator(s) in the FoV is a basic requirement for this observation, ie. multiple-beam capability is a must (1 target + 3 calibrators). VLBI Low frequency array is currently in development. Fringes between MWA and uGMRT were demonstrated recently (Kirsten et al. 2016). Few telescopes will have low frequency capability (e.g. uGMRT, FAST, Miyun, Past and Tianlai, etc.), with limited uv coverage, image reconstruction algorithms for low frequencies will need to be improved.

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2. Björnsson, C.-I.; Keshavarzi, S. T. 2017, ``Inhomogeneities and the Modeling of Radio Supernovae”, 2017 ApJ 841, 12.

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

1.4 PSR-ASTR-LOW: SKA-Low precise astrometry of Low-Frequency Pulsars

PROJECT DETAILS	
Title	**SKA-Low precise astrometry of Low-Frequency Pulsars**
Principal Investigator	**Richard Dodson**
Co-Authors	**Maria Rioja, Charlotte Sobey**
Time Request	16,000

FACILITY		Preconditions
X	SKA1-LOW	Observations to be arranged jointly with a VLBI array.
	SKA1-MID	

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	16hr (4x4) per target
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	4 epochs over a 1-2 year period close to the date where the parallax signature is largest (March and September)
	Time-critical override	
	Custom Experiment	
X	Commensal	Commensal fast transient observations could make use of the voltage data to follow up candidates. Simultaneous pulsar timing processor in order to refine the target pulsar(s) ephemeris.
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW array interferometer images, for accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. This project will use Multi-View technique, refer to M-VIEW case (1.1) for requirements.

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

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Significant numbers of pulsars have steep spectral indices, especially those detected in low-frequency pulsar surveys, and, therefore, can only realistically be observed below ~350 MHz [1,2]. These also precisely probe the nearby ISM. The measurement of RM is easy, but parallax distances are challenging at these frequencies. The combination of RM and distance allows the measurement of the ISM in 3D to high precision. Low frequency astrometry to ~300 of the beam at 300MHz should be possible using MultiView [3,4]. This technique reduces the ionospheric residuals to ~1milliTECU, which is sufficient to measure the distance to close (<1kpc) pulsars to better than 8%. LOFAR has detected 100s of such pulsars, so we assumed SKA will detect 1000s. 1000 pulsar probes of the local magnetic on the plane (1 pulsar per degree for |b|<2) will allow a exquisite reconstruction of the 3D magnetic-field structure.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	1000	
Positions of targets	Individual targets within a single FoV of individual SKA1-LOW station	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ………………………………………..]
	X	NO
Time Critical?		YES [details: ………………………………………..]
	X	NO
Integration time per target (hrs)	4 epochs, 4 hours per target: 16,000hrs	
Average peak flux density (Jy or Jy per beam)	1mJy	
Range of peak flux densities (Jy or Jy per beam)	100mJy to 1mJy . Extrapolated from [1].	
Expected polarised flux density (expressed as % of total)	10%	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Temporal resolution (in seconds)	Standard Nyquist sampling

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OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	300 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Spectral resolution (kHz)	Standard for Low correlator continuum
Temporal resolution (in seconds)	Pulsar binning mode

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	8 (7 cals + 1 target)	
Required angular resolution of a tied array beam (arcmin)	178/25.5 arcsec (50/350MHz, 600/86cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~0.1 mJy in 1 min	
Primary beam size (FWHM, arcmin)	40m stations 10deg/1.4deg (50/350MHz, 600/86cm)	
Total bandwidth for each tied array beam	256 MHz (equivalent to 2 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	4	
Output bandwidth (minimum and maximum frequency - MHz)	64 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-LOW local interferometer data)	
Required angular resolution (arcmin) (single value or range)	Several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies
Maximum baseline required (km)	Full array
Mapped image size (degrees)	Standard FoV
Required pixel resolution (arcseconds)	standard
Number of output channels	standard
Output bandwidth (minimum and	256 MHz bandwidth

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maximum frequency - MHz)		
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-LOW continuum sensitivities (from 10 to 160 μJy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	25 mas to 0.2 arcsec depending on observing frequency	
Mapped image size (degrees)	Up to 5x5 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~0.1 mJy in 1 min	
Dynamic range within image (if polarisation products required define for each)	>=200 for primary target (to match thermal and ionospheric limits). Calibrators should be better than 60 per baseline per minute.	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-LOW will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-LOW interferometer images from the full array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec level.
Description of pipeline	Standard imaging pipeline for SKA1-LOW, standard VLBI pipelines for SKA-VLBI data (e.g. LOFAR plus international station observations)
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	Not time critical; similar cadence as for the external VLBI correlator (e.g. 1-2 months).

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Multiple tied array VLBI beams can provide interpolated astrometric solutions for the target line of sight. The quality of using planar solutions has been demonstrated [3]. Recent studies [4,5], from MWA site, show that (within a ~0.5deg FoV, for MWA baselines <6km) for more than 90% calibration success rate we need 2D surfaces, i.e. **6 beams (5 cals + 1 target)** to allow for the solution for curvature in the dTEC surface. (Studies to provide more statistics of the MWA solutions are required to improve this estimate.) To achieve the potential thermal accuracies calibrator behaviour has to be addressed. For that we need more than the minimum number of beams. An additional two (1 per dimension) will allow these checks. Thus we would recommend **8 beams (7 cals + 1 target)** for ultra precise astrometry.

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Calibration of multiple tied array beams requires direction dependent solutions. The dTEC surface over the core of the array would provide these solutions. Therefore the **real time DD solutions will need to be solved for, fitted, and applied** to the tied-array beams. Estimates of the area which can be summed together requires characterisation of the dTEC surfaces at SKA sites. From the MWA observations we find dTEC differences of 20mTEC over 6km as typical. These data suggests that a low order polynomial fit to the dTEC surface will be sufficient to provide the DD solutions for the tied array beams. The studies to provide robust statistics of the MWA solutions will improve this supposition.

Refer to M-VIEW case (1.1) for extended requirements.

REFERENCES

1) Bilous A 2018, A&A, *LOFAR census of non-recycled pulsars: profiles, DM, flux densities, and spectra* ***2016A&A...591A.134B***
2) Sobey, C. et al. 2019, MNRAS, *Low-frequency Faraday RMs towards pulsars using LOFAR: probing the 3-D Galactic halo magnetic field* ***2019MNRAS.484.3646S***
3) Rioja et al. 2017; *MultiView High Precision VLBI Astrometry at Low Frequencies*, **2017AJ....153..105R**
4) Rioja et al. 2019; *Astrometry Review*, A&AR, in prep
5) Dodson et al. 2018; *Investigations on MultiView VLBI for SKA*, **PoS(EVN2018)086**

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

1.5 EXOPL-ASTR-LOW: Precise astrometry for exoplanets detection with SKA1-LOW and VLBI

PROJECT DETAILS	
Title	**Precise astrometry for exoplanets detection with SKA1-LOW and VLBI**
Principal Investigator	**Jose Carlos Guirado**
Co-Authors	**Richard Dodson, Izaskun Jiménez-Serra, Maria Rioja**
Time Request	~4800hrs (assuming ~200 targets x 3 epochs)

FACILITY		Preconditions
X	SKA1-LOW	Observations to be arranged jointly with a VLBI array.
	SKA1-MID	

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	8hrs per target x 3 epochs
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	Planets period range between several years to tens of years (assuming an M star with 0.2Msun), therefore at least 3/obs/year.
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW array interferometer images, for accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. Need at least 1+7 VLBI beams for 1 target and 7 calibrators for 1 microarcsec astrometry. Refer to M-VIEW case (1.1) for Multi-view requirements.

POLARISATION PRODUCTS REQUIRED: *BEAMFORMER (X) or SKA CORRELATOR ()*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U

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	YX		Stokes V
POLARISATION PRODUCTS REQUIRED: *BEAMFORMER () or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q
X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
SKA, in any of its realizations, will provide a comprehensive study of radio stars from well-defined samples. Many astrometric projects will benefit from a precise determination of the proper motion, parallax, and possible further perturbations of their trajectories. Microarcsecond astrometric signatures could be accurately sampled in both stellar and substellar objects, which would reveal the presence of low-mass stars, brown dwarfs or planets. The mass of these objects could be measured with high precision, without the ambiguities inherent to other methods, allowing a better characterization. SKA will certainly make boost this field of research, having the capability to detect from a Jupiter-like planet around a 1Msun star at 50 pc (100 microarcsec signature) to an Earth-like planet around a 0.2Msun star at 15 pc (1 microarcsec signature). This will constitute, for the first time, a robust astrometric contribution in the search for habitable planets, one the outstanding goals of astronomy.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	Thousands of targets, with ~hundreds M type low-mass stars, and ~tens with magnetic activity (from Gagne et al.). To focus on strongest targets for high precision astrometry.	
Positions of targets	Individual targets within a single FoV of individual SKA1-LOW station, from Gaia catalogs.	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	20 microJy/beam level for 60sec integration, 1-sigma, and FAST remote telescope. 8h integration times to reach 1 μJy	
Average peak flux density (Jy or Jy per beam)	~10 μJy	
Range of peak flux densities (Jy or Jy per beam)	1-10 μJy (10-20 pc)	
Expected polarised flux density (expressed as % of total)	A few %	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the	50, 350MHz

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entire range of the setup (MHz)	
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Spectral resolution (kHz)	Standard for Low correlator
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-LOW station, up to 8 (7 cals + 1 target) for 1 microarsec astrometry	
Required angular resolution of a tied array beam (arcmin)	178/25.5 arcsec (50/350MHz, 600/86cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min	
Primary beam size (FWHM, arcmin)	40m stations 10deg/1.4deg (50/350MHz, 600/86cm)	
Total bandwidth for each tied array beam	256 MHz (equivalent to 2 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	4	
Output bandwidth (minimum and maximum frequency - MHz)	64 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a ‘support image’ in the case of VLBI observations, for SKA1-LOW local interferometer data)	
Required angular resolution (arcmin) (single value or range)	Several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies
Maximum baseline required (km)	Full array
Mapped image size (degrees)	Standard FoV
Required pixel resolution (arcseconds)	standard
Number of output channels	standard
Output bandwidth (minimum and	256 MHz bandwidth

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maximum frequency - MHz)		
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-LOW continuum sensitivities (from 10 to 160 μJy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	25 mas to 0.2 arcsec depending on observing frequency	
Mapped image size (degrees)	Up to 5x5 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min	
Dynamic range within image (if polarisation products required define for each)	>10 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-LOW will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-LOW interferometer images from the full array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec level.
Description of pipeline	Standard imaging pipeline for SKA1-LOW, standard VLBI pipelines for SKA-VLBI data (e.g. LOFAR plus international station observations)
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	No time critical, similar cadence as for the external VLBI correlator (e.g. 1-2 months).

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Multiple tied array VLBI beams can provide interpolated astrometric solutions for the target line of sight. The quality of using planar solutions has been demonstrated (Rioja 2017), with 4 beams. A preliminary study of the level to which planar solutions are acceptable (Dodson 2018) finds, from MWA data and within a ~0.5deg FoV, planar solutions are good for 90% of the sky directions, for MWA baselines ~6km. The remaining 10% can be approximated by a plane with losses of ~10%. To improve on that, and additionally to account for calibrator structural changes, we would recommend 8 beams (7 cals + 1 target)

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for best multiview astrometry. To achieve the thermal limits of ~30uas, we will need to improve on the current MV estimates. Further work will be required to demonstrate this.

Calibration of multiple tied array beams requires direction dependent solutions, particularly for SKA-LOW. The dTEC surface over the core of the array would provide these solutions. Therefore the real time DD solutions will need to be solved for, fitted, and applied to the tied-array beams. Further studies to provide robust statistics of the MWA solutions will strengthen our conclusions.

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1.6 HI-ABS-LOW: HI absorption at sub-kpc scales in normal and active galaxies at high redshifts

PROJECT DETAILS	
Title	**HI absorption at sub-kpc scales in normal and active galaxies at high redshifts**
Principal Investigator	**Neeraj Gupta**
Co-Authors	**Raghunathan Srianand**
Time Request	200 hrs

FACILITY		Preconditions
X	SKA1-LOW	Observations to be arranged jointly with a VLBI array.
	SKA1-MID	

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	200 hrs (continuum and spectral line)
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW array interferometer continuum and spectral line images, for complementary studies of the target -total flux density integration-. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V

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POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Thanks to large multi-wavelength surveys, AGNs and galaxies have been detected out to redshifts of z ~8-10 (Venemans et al., ApJ, 851, L8). The large spectral line surveys with SKA will be able to detect reservoirs of cold HI gas associated with these AGNs in 21-cm absorption and from the interstellar medium (ISM) of intervening galaxies (e.g. Morganti et al. 2015, aska, confE, 134). In case of absorption associated with AGNs, the SKA-VLBI observations will be essential to resolve the distribution and kinematics of cold atomic gas at sub-kpc scales (Morganti et al. 2013, Science, 341, 1082). These are required to understand the role played by the cold gas in the triggering of AGN activity and the host galaxy ISM: the co-evolution of AGNs with host galaxies is still unclear and powerful radio jet may moderate flows of cold gas feeding the SMBH to attenuate AGN/ star-formation (SF) activity (negative feedback) or compress cold gas to enhance SF activity (positive feedback). The sub-kpc scale spectroscopy of 21-cm absorbers associated with normal (intervening) galaxies is essential to measure the parsec scale structure of cold gas to accurately measure the fraction of cold gas in galaxies and its evolution as a function of redshift (Kanekar et al. 2014, MNRAS, 438, 2131). The SKA-VLBI, for the first time, will enable sub-kpc scale spectroscopy of these absorbers at high-z. At present such observations have only been possible for a handful of absorbers at low redshifts (z<0.2; Gupta et al. 2018, MNRAS, 476, 2432).

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	10	
Positions of targets	Individual targets within a single FoV of individual SKA1-LOW station	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ………………………………………..]
	X	NO
Time Critical?		YES [details: ………………………………………..]
	X	NO
Integration time per target (hrs)	0.2 mJy/beam level for 60sec integration, full b/w, 1-sigma. 20 hrs per target	
Average peak flux density (Jy or Jy per beam)	500 mJy	
Range of peak flux densities (Jy or Jy per beam)	100 - 1000 mJy	
Expected polarised flux density (expressed as % of total)		

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Depending on target redshift
Total Bandwidth (MHz)	4 MHz for spectral line, 256 MHz for

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	continuum
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Depending on target redshift
Total Bandwidth (MHz)	4 MHz for spectral line, 256 MHz for continuum
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Spectral resolution (kHz)	For continuum use standard for Low correlator; for spectral line use zoom mode 1 with 0.226 kHz
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays		1
Number of tied array beams per subarray		Depends on number of targets/calibrators within a single FoV of individual SKA1-LOW station, up to 4 (1 target, 3 calibrators).
Required angular resolution of a tied array beam (arcmin)		178/25.5 arcsec (50/350MHz, 600/86cm and 4 km radius subarray)
Maximum baseline required (km)		8
Required baseline sensitivity		between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min, 256 MHz b/w
Primary beam size (FWHM, arcmin)		40m stations 10deg/1.4deg (50/350MHz, 600/86cm)
Total bandwidth for each tied array beam		4/256 MHz (equivalent to 32 Mbps/2 Gbps data rate for 2-bit sampling per VLBI beam)
Number of output channels		1/4
Output bandwidth (minimum and maximum frequency - MHz)		4/64 MHz per channel
Required rms (Jy) (if polarisation products required define for each)		N/A
Dynamic range (if polarisation products required define for each)		N/A
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-LOW local interferometer data)	
Required angular resolution (arcmin) (single value or range)	Several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies
Maximum baseline required (km)	Full array
Mapped image size (degrees)	10"x10"

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Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	256 MHz bandwidth (same as VLBI beams)	
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-LOW continuum sensitivities (from 10 to 160 μJy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth)		
Required angular resolution (arcmin) (single value or range)	Several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies	
Maximum baseline required (km)	Full array	
Mapped image size (degrees)	10”x10”	
Required pixel resolution (arcseconds)	standard	
Number of image channels	17k	
Channel width (kHz)	Zoom mode 1: 226 Hz for 4 MHz b/w	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	~3 mJy/beam in 1 min, 4 MHz b/w	
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	25 mas to 0.2 arcsec depending on observing frequency	
Mapped image size (degrees)	Up to 10x10 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min	
Dynamic range within image (if polarisation products required define for each)	>50 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
		5%

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	X	10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-LOW will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-LOW interferometer continuum and spectral line images from the full array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec level.
Description of pipeline	Standard imaging pipeline for SKA1-LOW, standard VLBI pipelines for SKA-VLBI Low frequency data (e.g. based on GMRT/LOFAR pipelines)
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	N/A

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
VLBI Low frequency array is currently in development. Fringes between MWA and uGMRT were demonstrated recently (Kirsten et al. 2016). Few telescopes will have low frequency capability (e.g. GMRT, FAST, Miyun, Past and Tianlai, etc.).

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REFERENCES
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1.7 SCINT-LOW: Pulsar Scintillometry at very low frequencies

PROJECT DETAILS	
Title	**Pulsar Scintillometry at very low frequencies**
Principal Investigator	**Franz Kirsten**
Co-Authors	**Dana Simard, Robert Main, Dan Stinebring, Ue-Li Pen, Jean-Pierre Macquart, Olaf Wucknitz**
Time Request	200

FACILITY		Preconditions
X	SKA1-LOW	Observations to be arranged jointly with a VLBI array.
	SKA1-MID	

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	200
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
X	Commensal	Simultaneous pulsar timing processor in order to refine the target pulsar(s) ephemeris.
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	20 km inner core -- as much collecting area as possible

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW array interferometer images, for accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. This project will also make use of the multi-beam capability for phase referencing between different calibrators to the target (refer to M-VIEW case -1.1- for detail requirements). VLBI should be possible with GMRT, FAST, MWA, other Asian antennas and possibly future space born dishes. In certain cases it might be of advantage to conduct the VLBI observations with SKA1-Low simultaneously with ones on SKA1-Mid, to trace scintillation across a widest possible bandwidth. This might only be possible with some pulsars, bright enough towards the upper

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end frequency (i.e. Mid) and with scintillation parameters that allow to resolve the scintils in the low frequency end (i.e. Low).

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
We would like to use SKA1-Low-VLBI to study pulsar scintillation to, eventually, resolve pulsar magnetospheres and constrain models of pulsar emission. We need VLBI to a) measure an accurate distance to the pulsar which we then use to b) measure an accurate distance to the scattering screen (Ds). Once we know Ds we can use the speckles on the scattering screen as stations in an interferometer that are several AU apart, i.e. have a tremendous resolving power (first pioneered by Brisken et al. 2010). This can then be applied to measure the physical size of the emission region of a pulsar. This has been tried before on B0834+06 (Pen et al. 2014). This only works on very bright targets; with SKA we could do this on many more sources that are fainter. Compared to the same project with SKA1-Mid, however, due to the steep frequency dependence of scattering this might only be possible at the upper end of SKA1-Low. The small decorrelation bandwidth at the lower frequencies (<1kHz) might not be resolvable. However, the size of the scattering disk is larger at longer wavelength (scales with lambda ^2), increasing the resolving power of the 'interstellar interferometer'.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	~100	
Positions of targets	Individual targets within a single FoV of individual SKA1-LOW station	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ………………………………………..]
	X	NO
Time Critical?		YES [details: ………………………………………..]
	X	NO
Integration time per target (hrs)	2 hrs per pulsar to collect enough scintils. (0.2 mJy/beam level for 60sec integration, 1-sigma)	
Average peak flux density (Jy or Jy per beam)	200 mJy/beam	
Range of peak flux densities (Jy or Jy per beam)	50 - 2000 mJy/beam	

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Expected polarised flux density (expressed as % of total)	10-100%

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Spectral resolution (kHz)	High-resolution visibilities ~2s, several kHz (external correlator concern)
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Spectral resolution (kHz)	Standard for Low correlator
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-LOW station, up to 8 VLBI beams per subarray (1 target, 7 calibrators)	
Required angular resolution of a tied array beam (arcmin)	178/25.5 arcsec (50/350MHz, 600/86cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min	
Primary beam size (FWHM, arcmin)	40m stations 10deg/1.4deg (50/350MHz, 600/86cm)	
Total bandwidth for each tied array beam	256 MHz (equivalent to 2 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	4	
Output bandwidth (minimum and maximum frequency - MHz)	64 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
		5%
		10%
	X	20-50%
		n/a

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IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-LOW local interferometer data)		
Required angular resolution (arcmin) (single value or range)	Several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies	
Maximum baseline required (km)	whole array	
Mapped image size (degrees)	standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	256 MHz bandwidth	
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-LOW continuum sensitivities (from 11□10^{-6} to 163□10^{-6} Jy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 − I, 30 − Q/U/V	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	
Required angular resolution (arcmin) (single value or range)	25 mas to 0.2 arcsec depending on observing frequency
Mapped image size (degrees)	Up to 5x5 arcsec per beam
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min
Dynamic range within image (if polarisation products required define for	>50 for primary target ~1000 for calibrators

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each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-LOW will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI to obtain high frequency resolution VLBI visibilities, and simultaneous SKA1-LOW interferometer images from the full array.
Description of pipeline	Standard imaging pipeline for SKA1-LOW Scintillation analysis pipelines for SKA-VLBI data
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.)	No time critical, similar cadence as for the external VLBI correlator (e.g. 1-2 months).

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
VLBI Low frequency array is currently in development. Fringes between MWA and GMRT were demonstrated on Crab giant pulses. LOFAR regularly performs VLBI with the international baselines. In the south, few telescopes will have low frequency capability (e.g. GMRT, FAST, MWA, Miyun, Past and Tianlai, etc. and possibly future space born dishes). Techniques for calibration at such low frequencies will need to be developed and will rely to a large degree on what has been done for LOFAR and MWA.

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

1.8 AGN-LOW: AGN Physics at very low frequencies in COSMOS

PROJECT DETAILS	
Title	**AGN Physics at very low frequencies in COSMOS**
Principal Investigator	**Leah Morabito**
Co-Authors	
Time Request	10000 hours

FACILITY		Preconditions
X	SKA1-LOW	Observations to be arranged jointly with a VLBI array.
	SKA1-MID	

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	10000 hours
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW array interferometer images, for complementary studies of the target at different angular scales and total flux density and polarization monitoring. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I

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X	YY	X	Stokes Q
X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Sub-arcsecond to milliarcsecond resolution imaging is critical for AGN studies. In radio loud AGN, it is necessary to reach high resolution to understand the particle acceleration mechanisms, for example in hot spots and working surfaces at the tips of nearby Fanaroff-Riley type II jets [1]. The frequency coverage of the SKA will enable robust spectral modelling of these mechanisms to pin down the exact physics of the interaction between jets and the ambient medium [2]. In more distant radio loud AGN, high resolution coupled with the SKA's excellent sensitivity will allow us to morphologically classify even the most distant radio sources [3,4] (z ~ 6), and study sub-populations of distant radio-loud AGN [5]. The greatest advances will be for radio-faint AGN. With its unprecedented sensitivity and high resolution, SKA-VLBI will help explore one of the most pressing open questions on AGN today: what is the source of radio emission in radio-quiet AGN? The radio emission is often attributed to either star formation [6] or AGN activity [7]. With mas resolution, we will be able to explore whether galaxy scale jets exist, study AGN outflows, and in some cases even pinpoint low-luminosity AGN which were otherwise not identified. SKA-VLBI will be crucial for determining the relative contributions of AGN and star forming galaxies to the sub-mJy population. Synchrotron emission produces a power law spectrum which is brighter at low frequencies, allowing us to reach intrinsically fainter sources. Additionally, spectral turnovers around 100 MHz due to either free-free absorption or synchrotron self-Compton absorption can only be observed at low frequencies. These observations will cover the 1 square degree COSMOS field, where there is excellent ancillary data to provide redshifts, photometric data, and radio coverage at higher frequencies (for calculating spectral index). The sensitivity has been chosen to match the sensitivity limit (assuming a typical spectral index of -0.7) of MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) Survey [8].

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (VLBI beams)
Number of targets	sub-mJy AGN population. Expect about 5000 per square degree.	
Positions of targets	Individual targets within a single FoV of individual SKA1-LOW station	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	8 uJy 1 sigma limit achieved in 11 minutes, 4h for appropriate UV sampling for imaging	
Average peak flux density (Jy or Jy per beam)	70 uJy/beam	
Range of peak flux densities (Jy or Jy per beam)	40 uJy/beam -- 80 mJy/beam	

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Expected polarised flux density (expressed as % of total)	A few %

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW band centre
Total Bandwidth (MHz)	256 MHz (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	50, 350MHz
Spectral resolution (kHz)	Standard for Low correlator (5.4 kHz)
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	Expect 1 targets/3 calibrators within a single FoV of individual SKA1-LOW station at bottom of band	
Required angular resolution of a tied array beam (arcmin)	178/25.5 arcsec (50/350MHz, 600/86cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min	
Primary beam size (FWHM, arcmin)	40m stations 10deg/1.4deg (50/350MHz, 600/86cm)	
Total bandwidth for each tied array beam	256 MHz (equivalent to 2 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	4	
Output bandwidth (minimum and maximum frequency - MHz)	64 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-LOW local interferometer data)	
Required angular resolution (arcmin) (single value or range)	Several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies

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Maximum baseline required (km)	Full array	
Mapped image size (degrees)	Standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	256 MHz bandwidth	
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-LOW continuum sensitivities (from 10 to 160 μJy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 − I, 30 − Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	25 mas to 0.2 arcsec depending on observing frequency	
Mapped image size (degrees)	Up to 5x5 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min	
Dynamic range within image (if polarisation products required define for each)	>50 for primary target ~1000 for calibrators	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%

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		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-LOW will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-LOW interferometer images from the full array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec level.
Description of pipeline	Standard imaging pipeline for SKA1-LOW, standard VLBI pipelines for SKA-VLBI data (e.g. LOFAR plus international station observations)
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	For SDP products no time critical, similar cadence as for the external VLBI correlator (e.g. 1-2 months). VLBI beam voltages need to be made available to the external correlator within several weeks after observation completion.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
To get practically thermal noise limited data on the primary target, having several 10 mJy calibrators in the FoV is a basic requirement for this observation, ie. multiple-beam capability is a must. VLBI Low frequency array is currently in development. Fringes between MWA and uGMRT were demonstrated recently (Kirsten et al. 2016). Few telescopes will have low frequency capability (e.g. GMRT, FAST, Miyun, Past and Tianlai, etc.), with limited uv coverage, image reconstruction algorithms for low frequencies will need to be improved.

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1.9 PSR-ASTR-MID: Parallax measurement of Southern Hemisphere pulsars

PROJECT DETAILS	
Title	**Parallax measurement of Southern Hemisphere pulsars**
Principal Investigator	**A. Deller on behalf of the Pulsar SWG**
Co-Authors	**The pulsar astrometry team**
Time Request	800 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	800
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	8 epochs over 18 months per source, 50 sources (spread in RA, but concentrated in the plane and towards the Galactic Centre).
	Time-critical override	
	Custom Experiment	
X	Commensal	Commensal fast transient observations could make use of the voltage data to follow up candidates. Simultaneous pulsar timing processor in order to refine the target pulsar(s) ephemeris.
X	Collaborative & Coordinated	Simultaneous availability of Long Baseline Array including Hartebeestok, EVN antennas, African VLBI Network antennas, and SKA1-MID
X	Sub-arrays required	Subarrays may be requested for some targets

COMMENTS ON OBSERVING STRATEGY
Observations will need to be fixed time, scheduled using SKA-VLBI access agreements, in order to enable the other elements of the VLBI array to participate. In order to sample the parallax signature most effectively, epochs will ideally observed within +/- 1 week of the optimal time, which depends on their right ascension. Some grouping of target sources is likely to be possible. Subarrays may be used for some bright targets (for which the full sensitivity is not required), enabling a normal SKA1-mid observation to take place while just

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a few antennas are used for SKA-VLBI. The assumed configuration of other participating VLBI stations is 5-10 25m-class stations + ASKAP; unless subarrayed, SKA1-mid dominates the sensitivity. For some bright and/or strongly scattered pulsars, observations at higher frequency may be used. More details are given in Paragi et al. (2015).

A bare minimum of 4 beams (3 calibrators + target pulsar) are needed for good calibration interpolation. However, additional calibration beams would enable a better spatial calibration interpolation in some cases, and add the possibility to identify and reject calibrators with time-variable structure. A typical number of VLBI beams might be 5 or 6, but the actual number will vary on a field by field basis.

Normal interferometer data should be produced from the SKA1-MID antennas participating in SKA-VLBI observations, to provide absolute amplitude calibration. VLBI visibilities can be used for this case.

The pulsar timing processor would be expected to run simultaneously in order to refine the target pulsar(s) ephemeris.

Every attempt should be made to ensure that the gain of the SKA1-mid voltage beams are as stable as possible, since these will likely be used to refine the pulsar ephemeris for the target pulsars (unless the pulsar timing backend at SKA1-mid can run in parallel to VLBI observing, which would be an even better solution).

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (_) or CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)

Parallax measurements of millisecond pulsars to obtain precision astrometry (position, proper motion and parallax), which will be used to improve the pulsar timing model for the system. This will enable improved strong-field tests of gravity, one of the key SKA science goals (Shao et al., 2015). Other science benefits include studying the neutron star equation of state and better modeling the Galactic electron density distribution (Han et al. 2015, Tauris et al. 2015, Janssen et al. 2015).

The necessary astrometric accuracy (and hence required S/N ratio on target) will depend on the distance to each individual system. Here we take 30 micro-arcseconds per epoch as a fiducial value, sufficient to yield a parallax accuracy of 10 micro-arcseconds and hence a distance accurate to 1% at 1 kpc / 10% at 10 kpc. Assuming a VLBI beam size of 6 mas, attaining 30 micro-arcsecond per-epoch accuracy requires a S/N ratio of 100. The required on-source time then depends on the target brightness; we have used 100 microJy as a fiducial value and assumed a pulse duty cycle of ~10% (meaning the “gated equivalent” flux density of 3x higher, or 300 microJy), which means a noise value of 3 micro-Jy is required – this will take 2 hours on-source. Some sources will require longer, many will not need this

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much time.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (VLBI beams)
Number of targets	50	
Positions of targets	Spread in RA and declination, but concentrated at lower Galactic latitudes for all but the closest pulsars. In Galactic longitude, many targets will be close to 0 degrees.	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?	X	YES to be observed close to desired dates for good sampling of parallax extrema
		NO
Integration time per target (hrs)	16 hours per source (8 x 2 hours per observation)	
Average peak flux density (Jy or Jy per beam)	100 microJy (assumed pulse duty cycle ~10%, corresponding to an equivalent peak flux density of 300 microJy after pulsar gating)	
Range of peak flux densities (Jy or Jy per beam)	60 microJy minimum (would take 6 hours per obs), ~few mJy maximum (no longer sensitivity-limited, could be as short as 30 min per observation)	
Expected polarised flux density (expressed as % of total)	Varies depending on source up to close to 100%; not important for the science case.	

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	1.6 GHz
Total Bandwidth (MHz)	500 MHz
Minimum and maximum frequency over the entire range of the setup (MHz)	1250-1750 MHz
Spectral resolution (kHz)	Standard continuum standard spectral resolution, e.g. 0.5 MHz (spectral resolution for VLBI visibilities is 200 kHz)
Temporal resolution (in seconds)	Standard continuum temporal resolution, e.g. 1 s
OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR ( )*	
Central Frequencies (MHz) (including redshift, observatory correction)	1.6 GHz
Total Bandwidth (MHz)	500 MHz (4 Gbps for 2-bit sampling, per VLBI beam)
Minimum and maximum frequency over the entire range of the setup (MHz)	1250-1750 MHz
Spectral resolution (kHz)	16, 32, 64, 128 or 200 MHz bands ("VDIF" VLBI output format).
Temporal resolution (in seconds)	Nyquist sampled

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NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-MID dish, a minimum of 4 VLBI beams per subarray (e.g. 1 target, 3 calibrators) but preferably 8 (i.e. 1 target, 7 calibrators)	
Required angular resolution of a tied array beam (arcmin)	May be observation specific, but by far the most common case will be ~0.05 arcmin (by going to the maximum baseline practical before re-phasing starts to become a problematic overhead).	
Maximum baseline required (km)	In the most common case, ~15 km or so. Needs to be user-selectable on a per-observation basis to allow control over the tied array beam size (in some cases, a shorter max baseline and hence larger tied array beam will be desirable to fit several targets into a single beam) and how frequently the array needs to be recalibrated.	
Required baseline sensitivity	Between SKA1 VLBI beam (8 km baselines) and a 100m-class dish is ~35 μJy in 1 min, for 500 MHz b/w.	
Primary beam size (sq degrees)	0.5	
Total bandwidth for each tied array beam	500 MHz (4 Gbps for 2-bit sampling, per VLBI beam)	
Number of output channels	Depends on the output subband bandwidth. For a default case of 32 MHz bands, this equates to 16 subbands x 2 polarisations.	
Output bandwidth (minimum and maximum frequency - MHz)	Minimum 16 MHz, maximum 128 MHz (set based on the capabilities of the other VLBI antennas participating.), with the caveat that these tuneable channels should lie within the 200 MHz frequency slice boundaries.	
Required rms (Jy) (if polarisation products required define for each)	Not directly applicable.	
Dynamic range (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations)	
Required angular resolution (arcmin) (single value or range)	0.01-0.1.
Maximum baseline required (km)	Set to the same value as is used for the formation of the VLBI beam, so typically ~15 km. If the more distant stations can also be included, that is welcome, but not required.
Mapped image size (degrees)	1

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Required pixel resolution (arcseconds)	0.5 (for the canonical case of 15 km max baseline)	
Number of output channels	10 (to provide basic spectral index information for sources in the field)	
Output bandwidth (minimum and maximum frequency - MHz)	1250-1750 MHz	
Required rms (Jy per beam) (if polarisation products required define for each)	3e-6 for a typical observation of ~2 hour	
Dynamic range within image (if polarisation products required define for each)	100,000 to 500,000	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (VLBI)		
Required angular resolution (milliarcseconds) (single value or range)	5-10	
Mapped image size (arcseconds)	5 (set by the tied array beam size of SKA1-mid)	
Number of image channels	10	
Channel width (kHz)	50,000	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	Typically ~10e-6 (depends on the pulsar brightness and hence observation time. Most stringent case will approach 5e-6)	
Dynamic range within image per channel (if polarisation products required define for each)	100,000	
Absolute flux scale calibration		1-3%
	X	5%

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		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Correlator: standard Beamformer: Will use standard VLBI techniques.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	Production of flag table covering timeranges where beamformer sum is no present (e.g., slewing) or corrupted (e.g., due to failed antenna). Production of estimated system temperature table for beamformer sum, for use in VLBI processing.
Data products	Correlator: standard Beamformer: VDIF baseband data (includes metadata eg time stamps. Description of VDIF standard is available at http://vlbi.org/vdif/)
Description of pipeline	Correlator: standard Beamformer: Realtime data transport to VLBI correlator (could be in Perth, Hobart, Europe…) this requires 20 Gbps link for realtime correlation (for 4 VLBI beams). Alternative is recording to harddisk at the Science Processing Centre (based in Cape Town), and posterior internet transfer to the external correlation.
Quality assessment plan & cadence	Records of delays, phases, fringe rates, amplitude calibration corrections that can be used to estimate sensitivity and compared to nominal values. Feedback will be supplied after VLBI correlation and analysis, and should be provided for every observation. The time to VLBI correlation will dominate the lag between observation and the provision of feedback – the quality assessment should be an integral part of the correlation process.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	For the VLBI data itself, obviously this needs to be available in real time (e-VLBI preferred). For the commensal SKA1 imaging, this can be upon completion of the scheduling block and pipeline reduction

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ISSUES TO BE DETERMINED/RESOLVED
(Here you should include any additional information that needs to be resolved before this science can be carried out)

Most importantly, agreements covering the proposing and scheduling of VLBI observations need to be made. The LBA, EVN, GMRT and EAVN are all potential partners for VLBI observing and expertise. The location of the VLBI correlator and hence the manner in which SKA1-mid baseband data is transported to the correlator (via high-speed network in real time, buffer + slower than real-time network, network partway + transportable media hybrid, …) remains to be determined.

The availability of other VLBI-capable antennas in Africa has the potential to strongly influence the available uv coverage for VLBI observations (which although not directly critical for point-source astrometry, does impact the ability to model calibrator sources and minimise source structure effects).

The production of flag and system temperature tables for use during VLBI data reduction is described in the Interface Control Document with the Telescope Manager but will need to be refined during the commissioning period.

CSP correlator resources are limited. For Band 2 observations one could use:

1. 3 FSPs for 500MHz (actually 600 MHz) continuum imaging (standard resolution 13.44 kHz). Polarisation maps are not required, but could be useful for commensal science.
2. 3 FSPs for one 500MHz (actually 600 MHz) pulsar timing beam
3. Transient buffer voltage data is done at the VCC level (Very Coarse Channelizers) for every antenna output, before the FSP processing, in 1 or 2x300 MHz search windows. Therefore, it does not consume FSP resources.
4. The remaining FSPs can be used for VLBI beams, with a maximum of 12 beams (using 18 FSPs). Together with the VLBI beams one gets VLBI visibilities with 200 kHz resolution from the same array/subarray that was phased-up to produce the beams. If this resolution is enough, it is not needed to set up FSPs for normal imaging, getting a maximum of 14 VLBI beams (using 21 FSPs).
5. 2 FSPs are not used.

Selection of the number and bandwidth of the sub-bands (i.e. beam-channels) for the VLBI beams, will be done depending on compatibility with the VLBI array.

Size if the subarray needs to be user-selectable on a per-observation basis to allow control over the tied array beam size (in some cases, a shorter max baseline and hence larger tied array beam will be desirable to fit several targets into a single beam) and how frequently the array needs to be recalibrated.

REFERENCES

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1.10 GAL-METH: Galactic Structure using maser parallax measurements

PROJECT DETAILS	
Title	**Galactic Structure using maser parallax measurements**
Principal Investigator	**Simon Ellingsen**
Co-Authors	**Andreas Brunthaler, Huib van Langevelde, Hiroshi Imai**
Time Request	1500 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	100% of SKA1-mid collecting area phased up, simultaneous availability of LBA (Long Baseline Array), AVN (African VLBI Network) and EVN (European VLBI Network) antennas.
	SKA1-SURVEY	

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	1500

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	4 epochs over a 1-2 year period close to the date where the parallax signature is largest (March and September)
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	Simultaneous availability of Long Baseline Array (Australia), African VLBI Network and European VLBI Network antennas with 6.7 GHz receiver capability
	Sub-arrays required	

COMMENTS ON OBSERVING STRATEGY
Scheduling commensal with VLBI network. At least 4 phased beams required, 3 for calibrators, 1 for target. For some targets up to 14 beams could be utilized if available. Observe International Celestial Reference Frame (ICRF) sources for tropospheric calibration of the VLBI array. Primary output is VLBI-formatted beamformed data. It is desirable to collect SKA1-MID continuum and spectral line imaging data in parallel for comparison with the VLBI data, this requires a zoom band with a spectral resolution of 2.2 kHz (0.1 km/s at 6.7 GHz), for example 2 MHz with 1024 spectral channels. Sources need to be observed at

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4 epochs spread over 18-24 months at times when the parallax signature is greatest. This case uses in-beam phase referencing: the 8 microJy sensitivity requirement assures at least 3-4 calibrators within the primary beam of a 25m antenna at ~6.7 GHz.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or CORRELATOR (_)*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (__) or CORRELATOR (X)*			
	XX	X	Stokes I
	YY		Stokes Q
	XY		Stokes U
	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Parallax measurements of interstellar masers can provide accurate (4% at 8 kpc) distances to the population of young, high-mass star formation regions which define the spiral arms (e.g. Reid et al. 2017). This project will measure parallax distances to 300 southern sources to obtain a southern sample equivalent to those currently being obtained in the northern hemisphere. These observations will produce the most accurate measurements to date of the basic Galactic parameters such as the radius and speed of rotation of the solar system about the Galactic centre and also of the distances to the individual star formation regions. We are seeking an astrometric accuracy of 5 µas from 4 epochs of observing, which provides distances accurate to 1% for sources at 2 kpc (the nearest spiral arm), falling to 5% at 10 kpc. We will select 6.7 GHz methanol maser targets with a peak flux density greater than 0.7 Jy and a background quasar stronger than 0.5 mJy within the SKA1-mid FoV (Reid et al. 2017). A single epoch astrometric accuracy of 10 µas (to achieve 5 µas over 4 epochs) requires an SNR of 60, hence an RMS noise level in the continuum images of 8 µJy/beam (Reid & Honma, 2014). This requires 1 hour on-source per field per epoch.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (VLBI beams)
Number of targets	300 6.7 GHz methanol masers covering a range of Galactic longitudes and LSR velocities.	
Positions of targets	Galactic plane covering full range of longitudes visible from the southern hemisphere.	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………….]
	X	NO
Time Critical?	X	YES [details: Observations required near the equinoxes to maximise the amplitude of the parallax signal. Time window is of the order of 4 weeks]
		NO
Integration time per target (hrs)	60 minutes per field per epoch.	
Average peak flux density	0.5 mJy for in-beam background quasar.	

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(Jy per beam)	
Range of peak flux densities (Jy per beam)	Expect 3 sources per field stronger than 0.15 mJy
Expected polarised flux density (expressed as % of total)	Small, few percent maximum

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	6666 – 6672 MHz
Total Bandwidth (MHz)	500 MHz (dual polarization)
Minimum and maximum frequency over the entire range of the setup (MHz)	Exact values not important, but will utilise as large a spread in bandwidth as can be accommodated by the receiver/backend hardware to obtain optimal calibration of the zenith tropospheric delay
Spectral resolution (kHz)	2 kHz for 2 MHz around maser frequency, standard continuum for full 500 MHz band (external correlator concern)
Temporal resolution (‘dump’ time in s or ‘standard’)	Standard Nyquist sampling
OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	6666 – 6672 MHz
Total Bandwidth (MHz)	500 MHz (dual polarization)
Minimum and maximum frequency over the entire range of the setup (MHz)	Exact values not important, but will utilise as large a spread in bandwidth as can be accommodated by the receiver/backend hardware to obtain optimal calibration of the zenith tropospheric delay
Spectral resolution (kHz)	2 kHz for 2 MHz around maser frequency in a zoom window, standard continuum for full 500 MHz band
Temporal resolution (‘dump’ time in s or ‘standard’)	Standard, 1s

NON-IMAGING SPECIFIC CONSIDERATIONS	
Number of subarrays	1 (whole array)
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-MID dish, up to 14 VLBI beams per subarray (e.g. 3 targets, 11 calibrators)
Required angular resolution of a tied array beam (arcmin)	0.1 arcseconds or larger
Maximum baseline required (km)	N/A, phasing of full array
Required baseline sensitivity	~20 μJy/beam (SKA1-mid to 25m class antenna).
Primary beam size (sq degrees)	0.015 square deg (SKA1-mid 6.7 GHz FoV)
Total bandwidth for each tied array beam	500 MHz (4 Gbps for 2-bit sampling, per VLBI beam) (preferably 6.4 – 6.9 GHz, but exact range not important as long as it includes the 6.7 GHz methanol line).
Number of output channels	1024 spectral channels

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	3 (200 MHz each centred at the centre frequency of the future 256MHz standard channels for the VLBI stations)
Output bandwidth (minimum and maximum frequency - MHz)	6400 – 6900 MHz
Required rms (Jy) (if polarisation products required define for each)	8 μJy beam^{-1}
Dynamic range (if polarisation products required define for each)	60:1
Absolute flux scale calibration	1-3%
	5%
	X 10%
	20-50%
	n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-mid local interferometer data using coarse VLBI visibilities)		
Required angular resolution (arcmin) (single value or range)	0.08 arcsec	
Maximum baseline required (km)	N/A, whole array	
Mapped image size (degrees)	0.015 square deg (SKA1-mid 6.7 GHz FoV)	
Required pixel resolution (arcseconds)	Standard for normal visibilities (13.44 KHz)	
Number of output channels	1024	
Required rms (Jy per beam) (if polarisation products required define for each)	100 μJy beam^{-1}	
Dynamic range within image (if polarisation products required define for each)	60:1	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth)	
Required angular resolution (arcmin) (single value or range)	0.08 arcsec
Maximum baseline required (km)	N/A, full array
Mapped image size (degrees)	0.015 square deg (SKA1-mid 6.7 GHz FoV)
Required pixel resolution (arcseconds)	0.01 arcsec
Number of image channels	1024
Channel width (kHz)	2.2
Required rms (Jy per beam per channel) (if polarisation products required define for each)	1.2 mJy beam^{-1}
Dynamic range within image per channel	600:1 – 6000 : 1 (depending on source)

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(if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (VLBI)		
Required angular resolution (arcmin) (single value or range)	1.2 milliarcseconds (8000 km VLBI baselines at 6.7 GHz)	
Single Field-Of-View or mapped image size (degrees)	1 arcsecond for each phased-array beam (one for maser sources), remaining on background calibrator targets within FoV	
Number of image channels	1024 (maser) / 1024 (calibrators)	
Channel width (kHz)	2.2 kHz (maser) / 500 kHz (calibrators)	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	1.2 mJy $beam^{-1}$ (maser) / 8 μJy $beam^{-1}$ (calibrators)	
Dynamic range within image per channel (if polarisation products required define for each)	600 – 6000:1 (maser) / 60:1 (continuum)	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Correlator: standard and spectral line Beamformer: Will use standard VLBI techniques
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	Flag data for antennas off-source
Data products	Correlator: standard and spectral line Beamformer: VDIF baseband data (includes metadata eg time stamps. Description of VDIF standard is available at http://vlbi.org/vdif/)
Description of pipeline	Correlator: standard and spectral line Beamformer: Streaming of data to appropriate VLBI correlator. Data rate for phased SKA-mid is 4 Gbps per beam, although project could utilise higher data rates, if they were available. Data from outstations (LBA, AVN etc) also to be streamed to VLBI correlator site.
Quality assessment plan & cadence	Records of delays, phases, fringe rates

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Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.)	Upon completion of scheduling block and pipeline reduction.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Requirements for this project are very similar to those for “Parallax measurements of southern hemisphere pulsars”. Specifically, an accurate frequency standard (e.g. hydrogen maser) at each VLBI site. For in-beam calibration it is desirable if as many VLBI sites as possible have the same FoV as the SKA1-mid antennas, this technique is more complicated for a heterogeneous VLBI array. For heterogeneous arrays with some larger diameter (smaller FoV) antennas in-beam phase calibration will only be possible for a subset of sources where suitable calibrators are within the FoV of the larger antennas. CSP Mid correlator processing resources are limited, the number of VLBI beams will have to be chosen depending on the characteristics of the target field, allowing enough correlator resources for simultaneous SKA1-MID continuum (using 3 FSPs) and spectral line imaging (using 1 FSP). A maximum of 14 VLBI beams with 500 MHz b/w will be available for this case (using 21 FSPs from a total of 26 available).

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

1.11 WIDEF: Adding high angular resolution to SKA surveys through wide-field-VLBI technique

PROJECT DETAILS	
Title	**Adding high angular resolution to SKA surveys through wide-field-VLBI technique**
Principal Investigator	**Marcello Giroletti**
Co-Authors	**Zsolt Paragi, Tuomas Savolainen, Iván Agudo, Tao An, SKA-VLBI-science Working Group**
Time Request	2500

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Forming multiple beams; standard VLBI data format output; VLBI data streaming; coordination with EVN, AVN, LBA

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
X	SKA1-MID Band 2	500-2000
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
X	Commensal	The project would be carried out in combination with the SKA1-MID surveys thanks to simultaneous correlation and beam-forming of the data

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X	Collaborative & Coordinated	VLBI network such as LBA, AVN, EVN will provide time and correlation facilities, which requires coordination
X	Sub-arrays required	Beamforming performed from a subarray with different radius

COMMENTS ON OBSERVING STRATEGY
We envisage two possible strategies, one that can only be applied to a deep field, and a second one that is applicable to both a deep and a wide-field survey: *1)* *(blind survey)* the goal is to image with high angular resolution the entire 0.5deg x 0.5deg central area of a SKA1-MID deep field. The deep survey itself will be carried out with a total time of ~1000 SKA1-MID hours on a single 1deg^2 field. At the same time, multiple beams would be formed, and each of them would be correlated with the simultaneous data taken by the coordinated VLBI dishes. The multiple beams are iteratively formed on several pointing positions in order to cover as large as possible an area. With 4 beams, it is reasonable to cover the central 0.5deg x 0.5deg; with more beams (e.g. 16), it would be possible to cover the entire deep field (in a balanced trade off with sensitivity). *2)* *(targeted survey)* in this complementary strategy, the VLBI data are only taken on a target list that is iteratively compiled as the SKA1-MID survey goes on. Beams are not formed with the goal of mapping the entire field at high angular resolution but only to correlate the data around catalogued sources. In the early sky visits, beams are formed and VLBI-correlated with phase centres on the relatively brighter sources, in the later observations fainter source fields are added. This strategy would then be applicable to both the deep and the wide SKA1-MID survey; in the latter case, the coverage would be limited to what actually feasible on the VLBI networks, with an approach similar to what carried out in the mJive project (Deller & Middelberg 2014)

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X)*			
X	X		Stokes I
X	Y		Stokes Q
			Stokes U
			Stokes V
POLARISATION PRODUCTS REQUIRED : *CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q
X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)

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The study of galaxy evolution over cosmic time is a topical area of activity for the SKA. The addition of sensitive long baselines to the continuum surveys carried out with the SKA will provide fundamental clues on the nature of the radio sources detected in the surveys themselves and described in Prandoni & Seymour (2015). In particular, brightness temperature can be used to discriminate between AGN activity and star formation. This will further provide an efficient method to select AGNs over a broad range of cosmic times and a tool to study the feedback processes between supermassive black holes and their host galaxy as they merge and evolve through cosmic time. Both radio quiet (yet not radio silent) and radio loud AGNs will be detected. Other science area that would greatly benefit are the search for dual/multiple supermassive black holes (Deane et al. 2015), intermediate mass back holes (e.g. Mezcua et al. 2014) and the study of LIRG/ULIRG.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (for VLBI)
Number of targets	2000 for the deep field	
Positions of targets		
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	0.5	
Average peak flux density (Jy or Jy per beam)		
Range of peak flux densities (Jy or Jy per beam)		
Expected polarised flux density (expressed as % of total)		

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	1400
Total Bandwidth (MHz)	500
Minimum and maximum frequency over the entire range of the setup (MHz)	

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Spectral resolution (kHz)	1000 (external correlator concern)
Temporal resolution (in seconds)	Nyquist sampling

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	14 VLBI beams with 500 MHz b/w allow simultaneous Imaging of whole Band 2 with standard frequency resolution (13.44 kHz). The maximum number of beams with 500 MHz b/w is 16 but simultaneous Imaging only with coarse visibilities (200 kHz).	
Required angular resolution of a tied array beam (arcmin)		
Maximum baseline required (km)	1 (for blind survey), 4 (for targeted survey)	
Required baseline sensitivity	Between SKA1 VLBI beam and a 100m-class dish is ~30-40 µJy/beam in 1 min, for 500 MHz b/w.	
Primary beam size (sq degrees)		
Number of output channels	3	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	6-7 uJy/beam	
Dynamic range (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations)	
Required angular resolution (arcmin) (single value or range)	standard for reference surveys with SKA1-MID Band 2 and above
Maximum baseline required (km)	Whole array

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Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of output channels		
Output bandwidth (minimum and maximum frequency - MHz)	Same 500 MHz bandwidth as for beamforming	
Required rms (Jy per beam) (if polarisation products required define for each)		
Dynamic range within image (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (VLBI)		
Required angular resolution (arcmin) (single value or range)	5 milliarcsec	
Mapped image size (degrees)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)	5-6 uJy/beam	
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Correlator: standard Beamformer: standard VLBI techniques
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	correlation with very long baselines, wide-field VLBI imaging
Data products	Beamformer: VDIF baseband data (includes metadata eg time stamps. Description of VDIF standard is available at http://vlbi.org/vdif/)
Description of pipeline	
Quality assessment plan & cadence	

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Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	Beam-formed data should be available for VLBI correlation. Electronic transfer of the data to the VLBI correlator could be done "a posteriori" or ideally (as will likely become standard practice at the SKA1 operational epoch) in real time (e-VLBI). For our strategy #2 approach, the target list needs to be updated as the SKA1-MID survey makes progress, so regular updates would be necessary; for a deep 1000hr pointing, this means every few days, for the wide shallow 3pi survey, once per month would be sufficient.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
a) The number of tied array beams available for VLBI. For 500 MHz b/w a maximum of 16 beams are available but this will use all Mid correlator processing resources not allowing imaging at standard frequency resolution (only with coarse VLBI visibilities). For 14 beams with 500 MHz b/w, there are resources left for Imaging whole Band 2 with standard frequency resolution (13.44 kHz). b) Different sizes for a core subarray will be used, 1 km baselines (0.5 Km radius) for the blind survey, or with 4 km baselines (2 km radius) for the targeted survey. With these subarray sizes, the size of the VLBI beams are ~43 arcsec or ~11 arcsec for 1.6 GHz. This means that either ~100 beams or ~1600 beams are needed to cover the primary beam of a 100m class antenna. Mid correlator resources are insufficient to cover this goal. c) VLBI beams need to be quickly re-pointed to different targets in the sky, to overcome previous limitation.

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1.12 YSCLUST-MID: Young Stellar Cluster Deep Field

PROJECT DETAILS	
Title	**Young Stellar Cluster Deep Field**
Principal Investigator	**M. Hoare**
Co-Authors	**Cradle of Life Team**
Time Request	1000 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Needs VLBI for one of the science goals. Some aspects would benefit from Band 5+.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	1000 hours

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	125 x 8 hour visits to build up the 1000 hours in total. Each epoch to be done with simultaneous VLBI to monitor and locate non-thermal components and measure parallax and proper motion of cluster members. The 4 VLBI beams would need to cycle around the number of VLBI targets within the single field of view during each epoch. The epochs of 8 hours would be spread out with a logarithmic distribution of cadence over 2-3 years.
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
	Sub-arrays required	

COMMENTS ON OBSERVING STRATEGY
Observations toward one field-of-view where we cover the low-mass star forming cluster ρ Oph A in the L1688 cloud in Ophiuchus. This single pointing contains 3 class 0, 5 class I, 6 class II and 2 class 3 sources within the 6' field of view in Band 5 (Gutermuth et al. 2009). A total of 1000 hrs of integration time in SKA1-mid Band 5 would allow us to map the dust continuum at a resolution of up to 35 mas or 4.8 au at the 138 pc distance of the rho Oph complex. Spectral index and polarization patterns will probe grain growth through the cm-size regime both in the terrestrial and Jovian planet forming zones at either side of the snow

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line. Simultaneously we will conduct a search for pre-biotic molecules in the cool outer regions of the disk on 100 au or arcsecond scales. Simulations show that we should be able to detect the faint emission of simple amino acids such as glycine, as well as to characterise the chemistry of its precursors, which also show a collection of transitions at centimetre wavelengths and are expected to be more abundant than glycine. We will simultaneously conduct time monitoring of flaring emission due to magnetic activity from the YSOs in the field of view and study the polarization and variability in any ionized jet emission associated with the YSOs. Simultaneous VLBI observations will identify and locate non-thermal flares as well as determining the 6D position-velocity structure of a subset of the sources in the cluster to test cluster formation models.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or CORRELATOR ()*			
X	X		Stokes I
Y	Y		Stokes Q
			Stokes U
			Stokes V

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (__) or CORRELATOR (X)*			
X	XX	**X**	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
The earliest stage of the planet formation process is the growth of dust grains from micron through millimetre to centimetre sizes. Sensitive cm-wave studies are the only way to fill the large gap in our understanding of the early growth of grains through the cm-size regime (Testi et al. 2014). SKA1-mid equipped with Band 5 receivers provides the resolution and sensitivity to map out the progress of these processes in the nearest systems. Radial variations in grain growth (Perez et al. 2012) can be studied both inside and outside the snow line – the traditional boundary between rocky and gas giant planet formation. Asymmetries in the disk can also reveal processes that assist grain growth (Perez et al. 2014). The deep field observation also enables a simultaneous very deep search for the building blocks of life such as amino acids in the outer regions of the actual disks where planets are forming. The detection of glycine in these regions, where incorporation onto comets and delivery onto terrestrial planets is possible, would represent a major milestone in Astrobiology. We will also simultaneously study the ionized jets and 6D phase structure of the young cluster to test star formation models.

‘TARGETS’ OF OBSERVATIONS		
Type of observation (what defines a ‘target’)		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (for VLBI)
Number of targets	1 field of view	
Positions of targets	The core of the rho Ophiuchus A cluster at RA=16:26:24 Dec=-24:23	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ………………………………………..]
	X	NO
Time Critical?	X	YES [details: Timing of the VLBI measurements and cadence for variability studies makes the relative timing of the epochs important but not the absolute

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	timing.]
	NO
Integration time per target (hrs)	1000 hrs toward one field-of-view
Average peak flux density (Jy or Jy per beam)	Average continuum flux density at 13 GHz is 0.2 μJy per 35 mas beam over the whole disk. Integrated flux is about 0.3 mJy over a 1.5 arcsec diameter disk. Line intensities of ~0.05-0.2 K in a 3”-beam for the glycine lines around 13GHz.
Range of peak flux densities (Jy or Jy per beam)	Peak continuum is about 10 μJy per 35 mas beam. Intensity drops to below a 3σ detection at around a radius of 0.5 arcsec from the centre of the disk. Glycine lines could be much weaker if freeze out onto grains is more than assumed.
Expected polarised flux density (expressed as % of total)	Flaring systems can be highly circularly polarized (~30%) and will be bright. Synchrotron components in the ionized jets can be linearly polarized at around the 10% level. The jets are brighter than the disc and so this should be easily detectable. The dust emission from the disk is polarized at around the 1% level at mm wavelengths and could be similar at cm wavelengths if large grains are present.

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	We will use the 5b receiver. At the top end of 5b we will use a 2.4 GHz continuum band centred at 14.0 GHz to cover the continuum from 12.8 to 15.3 GHz. At the bottom end we will place a 2 GHz band centred at 10.1 GHz and cover the 8.8 to 11.3 GHz continuum.
Total Bandwidth (MHz)	4.4 GHz for continuum
Minimum and maximum frequency over the entire range of the setup (MHz)	8.8 GHz to 15.3 GHz
Spectral resolution (kHz)	No zoom windows will be used. The 64k channels across the 4.5 GHz continuum bandwidth gives 70 kHz or 1.7 kms^{-1} channels which is sufficient for detecting molecular lines with similar widths.
Temporal resolution (in seconds)	The maximum dump time of 1.4 seconds is sufficient for the variability studies of flaring stars.

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR ( )*	
Central Frequencies (MHz) (including redshift, observatory correction)	We will simultaneously perform VLBI with 0.4 GHz bandwidth across the frequency range 8.3 to 8.8 GHz.
Total Bandwidth (MHz)	0.4 GHz for VLBI
Minimum and maximum frequency over the entire range of the setup (MHz)	8.3 to 8.8 GHz (exact frequencies decided depending on the VLBI network used)
Spectral resolution (kHz)	External correlator concern
Temporal resolution (in seconds)	Standard Nyquist sampling

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NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	Full array	
Number of tied array beams per subarray	At present we only have 3 targets that are detected with VLBI. However, we would want to target all the potential targets – currently the number stands at 16 in the fov but this will rise.	
Required angular resolution of a tied array beam (arcmin)	0.05 arcsec	
Maximum baseline required (km)	Phasing full array	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~40 μJy/beam in 1 min, for 0.5 GHz b/w	
Total bandwidth for each tied array beam	0.4 GHz (equivalent to 3.1 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	2	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	4 μJy in each 8 hour epoch	
Dynamic range (if polarisation products required define for each)	1000	
Absolute flux scale calibration		
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations)		
Required angular resolution (arcmin) (single value or range)	0.035 arcsec at 13 GHz	
Maximum baseline required (km)	150 km	
Mapped image size (degrees)	800 arcsec. Need to image the entire primary beam (and probably several sidelobes), to model the (time-variable) extragalactic background sources.	
Required pixel resolution (arcseconds)	0.012 arcsec	
Number of output channels	20 x 256 MHz wide channels covering full 5 GHz observed to derive the spectral index maps.	
Output bandwidth (minimum and maximum frequency - MHz)	256 MHz	
Required rms (Jy per beam) (if polarisation products required define for each)	80 nJy/beam	
Dynamic range within image (if polarisation products required define for each)	Of order 10^5 to account for background sources in the field of view at the 10 mJy level.	
Absolute flux scale calibration		1-3%

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	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth)		
Required angular resolution (arcmin) (single value or range)	3", corresponding to the whole disk where the emission is expected to arise.	
Maximum baseline required (km)	2 km	
Mapped image size (degrees)	~20 facets of 30 arcsec each centred on a PPD target within the fov.	
Required pixel resolution (arcseconds)	1"	
Number of image channels	64k	
Channel width (kHz)	70 kHz	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	27 μJy/beam per 70 kHz channel. This is equivalent to an rms of 14mK over two channels needed to detect the glycine lines at around the 5σ level.	
Dynamic range within image per channel (if polarisation products required define for each)	100	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (VLBI)		
Required angular resolution (arcmin) (single value or range)	1 milli-arcsecond (it's VLBI!)	
Mapped image size (degrees)	3 arcsec	
Number of image channels	1	
Channel width (kHz)	0.4 GHz	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	4 μJy in each 8 hour epoch	
Dynamic range within image per channel (if polarisation products required define for each)	1000	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	To calibrate the continuum and reach the high continuum dynamic range in the presence of background sources of order 10 mJy the full field of view will need to be imaged and perhaps a few sidelobes. Over the 1000 hour integration many of these background sources (and also other T Tauri type stars in the cluster) will also vary. Once a suitable calibration has been achieved on the

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	continuum this can be transferred to the spectral data. To fully search the spectrum for pre-biotic molecules, it is desirable that the full spectrum (64k channels) is provided. This implies large data rates and large data cubes. However, only a small fraction of the total field of view needs to be imaged in spectral mode just around the targets of interest. Multiple lines from other more abundant complex organic molecules (COMs) will likely be detected simultaneously. Appropriate software exists to assist in the identification of all molecular lines detected within the observations (e.g. XCLASS, Comito et al. 2005, or Weeds, Maret et al. 2011).
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	High wind speed data should be flagged. Reprocessing will be needed to refine the calibration and interpretation. After regions with strong lines have been identified then line-free regions of continuum can be defined in order to better determine the spatial variation of the continuum spectral index. May also find new sources in the deep continuum map that were not known about a priori and that will be re-examined for line emission
Data products	Continuum image and spectral index map for the full field of view. Spectral data cubes around ~30 small fields of interest. VLBI continuum maps around ~15 very small fields of interest. Time resolved continuum data around ~30 sources of interest.
Description of pipeline	TBC
Quality assessment plan & cadence	TBC
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.)	For the continuum and spectral line imaging this will be about 24 hours up completion of each 8 hour scheduling block. Similarly for the VLBI datasets. For the time variability studies this will be a few seconds.

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
VLBI capability needs to be available and to be used simultaneously with imaging with the full SKA1-Mid array. If 4 VLBI beams are assumed then we would put 1 VLBI beam on a calibrator and the other 3 on targets in the single field of view for a single 8 hour epoch. Assuming there are about 15 VLBI targets within the field of view then we would like to cycle the 3 VLBI target beams around all 15 targets during an 8 hour epoch. For the time variability studies then at present we have indicated that we would search down to the dump time scale of 1 arcsecond for fast flaring events. Given that the data cannot all be stored I presume that this is similar to slow transient searching mode where you have a few hours to look for and store the data around the transient objects. Given that the transient objects are bright non-thermal sources then they are likely to be also bright enough for VLBI. So there is a mode whereby during the runs with VLBI we would want to search the first half an hour or so of the imaging data to see if new VLBI targets have appeared and if so then switch a VLBI target beam onto them perhaps. SKA1-MID correlator processing resources are limited and do not allow for simultaneous Imaging at full b/w (i.e. 5 GHz, this uses all the resources!!) and additional VLBI beams. If just 4.4 GHz are observed in the continuum observations (just one of the band 5 feeds), there will also be resources for a maximum of 4 VLBI beams with 0.4 GHz b/w. But more VLBI beams (up to 30) would make the VLBI observations much more efficient and sensitive.

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1.13 GAL-OH: Exploration of the dynamics of the Galactic Bulge using OH maser parallax measurements

PROJECT DETAILS	
Title	**Exploration of the dynamics of the Galactic Bulge using OH maser parallax measurements**
Principal Investigator	**Hiroshi Imai**
Co-Authors	**Gabor Orosz, Ross A. Burns, Naoteru Goda, Tahei Yano, Yoshiyuki Yamada, Naoko Matsumoto**
Time Request	2000 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	75% of SKA1-MID collecting area phased up, simultaneous availability of LBA (Long Baseline Array), AVN (African VLBI Network) and EVN (European VLBI Network) antennas, plus 100% of the collecting area used for simultaneous imaging.
	SKA1-SURVEY	

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
X	SKA1-MID Band 2	2000
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	6 epochs over a 2.5 year period close to the date when the parallax signature is the largest (March and September)
	Time-critical override	
	Custom Experiment	
X	Commensal	Pulsar astrometry towards the Galactic Centre **Mapping thermal/maser OH lines**
X	Collaborative & Coordinated	Simultaneous availability of Long Baseline Array (Australia), African VLBI Network and European VLBI Network antennas with 1.6-1.7 GHz receiver capability
X	Sub-arrays required	75% of SKA1-MID collecting area phased up (8 km baselines)

COMMENTS ON OBSERVING STRATEGY
Scheduling commensal with VLBI networks. Need to observe International Celestial Reference Frame (ICRF) sources within 10 degrees from the Galactic centre in antenna nodding. At least 4 phased beams required, 1 for in-beam calibrator, 3 for targets. For some targets up to 14 beams could be utilized if they are to become available. Primary output is VLBI-formatted beamformed data, normal and spectral line imaging data should be taken in parallel. Sources need to be observed at 6 epochs spread over 30 months at times when the

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parallax signature is greatest (March and September). For mapping the circumstellar envelopes in OH, full arrays with the longest baseline (150 km) shall be used.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (_) or CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q
X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
This project will measure parallax distances and proper motions of 500 stars hosting hydroxyl maser sources to sample them in the 6-dimensional phase space (*X*, *Y*, *Z*, *VX*, *VY*, *VZ*) towards the inner Galactic bulge. The kinematic information will be used for elucidating the dynamics of the bulge in order to understand the co-evolution of the central massive black hole with the bulge. We are seeking an astrometric accuracy of 20 µas from each of 6 observation epochs using both in-beam and “WideView” astrometric techniques. They will provide distances accurate to 10% for sources at 10 kpc. We will select 1.6 GHz hydroxyl maser targets with a peak flux density greater than 0.3 Jy and a background quasar brighter than 2.0 mJy within the SKA1-MID FoV. The astrometric accuracy of 20 µas (to achieve 10 µas over 6 epochs) requires an SNR of 300, hence an RMS noise level in the maser and continuum images of 0.9 mJy/beam and 6.7 µJy/beam, respectively. This requires 1 hour on-source per field per epoch. The whole OH maser emission shall be mapped for determining the sizes of the circumstellar envelopes. Measuring Zeeman effects and linear polarization orientation of the masers will elucidate the magnetic fields of the circumstellar envelopes as a probe of the final evolution of the stellar interior that drives copious stellar mass loss and determines the mass recycle in the inner Milky Way Galaxy.

‘TARGETS’ OF OBSERVATIONS		
Type of observation (what defines a ‘target’)		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (for VLBI beams)
Number of targets	500 1.6 GHz hydroxyl masers	
Positions of targets	Within +/- 2 degrees of Galactic longitude and latitude	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………….]
	X	NO
Time Critical?	X	YES [details: Observations required near the equinoxes to maximise the amplitude of the parallax signal. Time window is of the order of 4 weeks]
		NO
Integration time per target (hrs)	1 hour per field per epoch.	

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Average peak flux density (Jy per beam)	2.0 mJy for in-beam background quasar.
Range of peak flux densities (Jy per beam)	Expect 3 sources per field stronger than 0.15 mJy
Expected polarised flux density (expressed as % of total)	Small, few percent maximum

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR ( )*	
Central Frequencies (MHz) (including redshift, observatory correction)	1480 MHz (maser lines at 1612, 1665, 1667, 1720 MHz)
Total Bandwidth (MHz)	500 MHz (dual polarization)
Spectral resolution (kHz)	1 kHz for 0.5 MHz around maser frequency, standard continuum for full 500 MHz band (external correlator concern)
Temporal resolution ('dump' time in s or 'standard')	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER ( ) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	1480 MHz, zoom window centred at maser lines (maser lines at 1612, 1665, 1667, 1720 MHz)
Total Bandwidth (MHz)	500 MHz (dual polarization) & 3.125 MHz minimum b/w for the zoom window
Spectral resolution (kHz)	standard continuum for full 500 MHz band (13.44 kHz) & 1 kHz for the zoom window
Temporal resolution ('dump' time in s or 'standard')	Standard, 1s

NON-IMAGING SPECIFIC CONSIDERATIONS	
Number of subarrays	1
Number of tied array beams per subarray	10 targets + 4 calibrators for VLBI.
Required angular resolution of a tied array beam (arcmin)	5.4 arcsec
Maximum baseline required (km)	8 (75% collecting area)
Required baseline sensitivity	Between SKA1 VLBI beam and a 100m-class dish is ~40 μJy/beam in 1 min, for 500 MHz b/w
Primary beam size (sq degrees)	0.015 square deg (SKA1-MID 1.6 GHz FoV)
Total bandwidth for each tied array beam	500 MHz (for calibrators, equivalent to 4 Gbps data rate for 2-bit sampling per VLBI beam)
Number of output channels (per polarisation)	3 (500 for spectral data at external correlator)
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel
Required rms (Jy) (if polarisation products required define for each)	6.7 μJy/beam (1h integration)

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Dynamic range (if polarisation products required define for each)	300:1	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-mid local interferometer data using coarse VLBI visibilities)		
Required angular resolution (arcmin) (single value or range)	0.005 arcmin	
Single Field-Of-View or mapped image size (sq degrees)	0.48 degrees (SKA1-MID 1.6 GHz FoV)	
Maximum baseline required (km)	150 (except the subarray for VLBI within 8 km)	
Mapped image size (degrees)	standard	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	500 MHz	
Required rms (Jy per beam) (if polarisation products required define for each)	6.7 μJy $beam^{-1}$ (expected 1.6 μJy $beam^{-1}$ in 1h)	
Dynamic range within image (if polarisation products required define for each)	300:1	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth)		
Required angular resolution (arcmin) (single value or range)	0.015 arcmin	
Single Field-Of-View or mapped image size (sq degrees)	0.48 degrees (SKA1-MID 1.6 GHz FoV)	
Number of image channels	3125	
Channel width (kHz)	1.0	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	0.9 mJy $beam^{-1}$	
Dynamic range within image per channel (if polarisation products required define for each)	300 : 1 (depending on source)	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (VLBI)	
Required angular resolution (arcmin)	12 milliarcseconds (3000 km VLBI

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(single value or range)	baselines at 1.6 GHz)
Single Field-Of-View or mapped image size (degrees)	1 arcsecond for each phased-array beam (one for maser), remaining on background calibrator targets within FoV
Number of image channels	1024 (maser) / 1024 (calibrators)
Channel width (kHz)	1.0 kHz (maser) / 500 kHz (calibrators)
Required rms (Jy per beam per channel) (if polarisation products required define for each)	0.9 mJy beam^{-1} (maser) / 6.7 μJy beam^{-1} (calibrators)
Dynamic range within image per channel (if polarisation products required define for each)	300:1
Absolute flux scale calibration	[ ] 1-3% [ ] 5% [X] 10% [ ] 20-50% [ ] n/a

DATA ANALYSIS	
Procedures required	Correlator: standard Beamformer: Will use standard VLBI techniques
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	Flag data for antennas off-source GPS data will be useful for atmospheric calibration
Data products	Correlator: standard Beamformer: VDIF baseband data (includes metadata eg time stamps. Description of VDIF standard is available at http://vlbi.org/vdif/) Moderate channel spacings (0.5-8 MHz) are suitable for cross correlation between the SKA1-MID and other stations with channel spacing compatibility.
Description of pipeline	Correlator: standard Beamformer: Streaming of data to appropriate VLBI correlator. Data rate for phased SKA1-MID is 4 Gbps per beam, although project could utilise higher data rates if available. Data from outstations (LBA, AVN etc) also to be streamed to VLBI correlator site.
Quality assessment plan & cadence	Records of delays, phases, fringe rates

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Requirements for this project are very similar to those for "Parallax measurements of southern hemisphere pulsars". Specifically, an accurate frequency standard (e.g. hydrogen maser) at each VLBI site. For in-beam calibration it is desirable if as many VLBI sites as possible have the same FoV as the SKA1-MID antennas, this technique is more complicated for a heterogeneous VLBI array. For such arrays with some larger diameter (smaller FoV) antennas in-beam phase calibration will only be possible for a subset of sources where suitable calibrators are within the FoV of the larger antennas. Maximum number of VLBI beams with 500 MHz b/w is 16, using 24 FSPs, with only 2 FSPs left. In this case, no resources would be available for normal imaging (3 FSPs). For normal imaging (3 FSPs) and one zoom window (1 FSP), the maximum number of VLBI beams

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available is 14. The number of the calibrators in the primary antenna beam will be less than 3, only which we need 500 MHz b/w. The remained VLBI beams shall have narrower bands. Selection of the number and bandwidth of the sub-bands (i.e. beam-channels) for the VLBI beams, will be done depending on compatibility with VLBI terminals.

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1.14 TRANS: Resolving (ultra-)relativistic outflows with SKA-VLBI (GW-EM counterparts, GRB, SNe, TDE, XRB, etc.)

PROJECT DETAILS	
Title	**Resolving (ultra-)relativistic outflows with SKA-VLBI (GW-EM counterparts, Gamma-ray Bursts, Supernovae, Tidal Disruption Events, X-ray binaries, etc.)**
Principal Investigator	**Zsolt Paragi**
Co-Authors	**Alexander van der Horst, Miguel Pérez-Torres, Tao An** for the VLBI working group
Time Request	750 hours (for VLBI monitoring of ~30 targets in 3 years)

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Forming multiple tied-array beams, monitored for phasing-up stability, shadowing and individual antenna data quality. Standard VLBI data format output, parallel local interferometer data products, VLBI data streaming (real-time e-VLBI or buffering+electronic shipment), and flexibility to target of opportunity observations as well as accurate calibration of the tied-array beams are required as well.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
X	SKA1-MID Band 4	depending on the target
X	SKA1-MID Band 5	750 hours

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	Cadence of the monitoring observations may depend on both the total flux density evolution and the apparent source size. For certain transients the first epoch will ideally be scheduled within 1-2 days of the initial radio detection, and we will have additional 4 epochs within a month (to probe jet deceleration in long-GRBs; to probe accretion / ejection physics in Galactic neutron star or black hole X-ray binaries). Normally extragalactic transients (including most SNe, TDEs and Gravitational Wave (GW) - Electromagnetic (EM) counterparts) will require monitoring of months-years timescales instead.
X	Time-critical override	SKA-VLBI observations triggered either from

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		another instrument (X-ray, optical or radio detection), or directly from an SKA1-MID detection.
	Custom Experiment	
X	Commensal	Possibly, with SKA1-MID transient follow-ups
X	Collaborative & Coordinated	Will have to coordinate the SKA-VLBI observations with radio observatories.
X	Sub-arrays required	beamforming for up 8 km baselines

COMMENTS ON OBSERVING STRATEGY
Rapid turnaround of results during the first epoch is essential, where the selection of best calibrators will be finalised. Later it will help define the best monitoring strategy. This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-MID array interferometer images, for complementary studies of the target at different angular scales and total flux density and polarisation monitoring. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (__X__) or CORRELATOR (_)*			
X	X (or RCP)		Stokes I
X	Y (or LCP)		Stokes Q
	XY		Stokes U
	YX		Stokes V

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (__) or CORRELATOR (__X__)*			
X	XX (linear products may be used by SDP for phasing-up the array / calibrating the beam-formed data)	**X**	Stokes I (total intensity and polarization maps from the simultaneous SKA1-MID array data have immediate scientific value)
X	YY	**X**	Stokes Q
X	XY	**X**	Stokes U
X	YX	**X**	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
[This Use Case describes a Target of Opportunity or triggered SKA-VLBI project to follow up extragalactic/Galactic synchrotron transients with SKA-VLBI. The original Use Case considered long-GRBs primarily - this is modified to include a broader range of transients, observed in a 3-year Transient VLBI follow-up KSP (possibly part of a general Transient KSP for the SKA). Updated: 14 May 2019] We propose to observe extragalactic (redshift up to ~ 0.15) and Galactic synchrotron transients with SKA1-VLBI at 3-5 epochs. The time scales will depend on transient types / individual cases. For example, a typical radio afterglow of a gamma-ray burst (GRB) is at the 100 μJy level within a day – few days after discovery. The radio afterglows initially have an inverted spectrum, indicating that they are still optically thick at GHz frequencies, and the flux density is expected to rise further. Milliarcsecond resolution data are highly valuable, because the only GRB for which the expansion was reliably measured with the VLBI technique is GRB 030329. Our goal is to probe the expansion of the blast wave on shorter timescales than for GRB 030329, allowing us for the first time to probe the ejecta while it is

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still in the ultra-relativistic phase. The excellent resolution and sensitivity of total intensity SKA-VLBI imaging will allow us to detect a source size of <50-250 μas (for resolution range 0.6-3 mas, and SNR>50), or ejecta proper motion in the 1-10 μas/month regime. In addition, full-Stokes SKA1-MID interferometer data will allow us to probe polarisation in the afterglow (~0.1% level for a 1 mJy source, close to the expected peak of the emission). These measurements will provide important constraints on theoretical models of ultra-relativistic outflows.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	Four. A primary target (~>100 μJy) plus ideally at least three ~>1 mJy calibrators (up to 7 calibrators if microarcsecond-precision astrometry is needed)	
Positions of targets	All within a single FoV of individual SKA1-MID dishes	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………………..]
	X	NO
Time Critical?	X	YES [details: details: Target of Opportunity requiring rapid response within a few days in some cases]
		NO
Integration time per target (hrs)	Minimum on-source integration time is 3 hours. (all targets simultaneously). One could obtain useful science data down to 1 hour integration time (especially on brighter targets), but ideally we would prefer a longer integration to build up *uv*-coverage. There may be some additional time required for setting up real-time e-VLBI. The total request is ~5-6h per observation.	
Average peak flux density (Jy or Jy per beam)	~10^{-3} Jy/beam peak brightness (at maximum)	
Range of peak flux densities (Jy or Jy per beam)	~10^{-4} -10^{-2} Jy/beam peak brightness	
Expected polarised flux density (expressed as % of total)	1%	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Primarily (depending on target): 5400 MHz (C-band 4900-5900 MHz) or 8800 MHz (X-band 8300-9300 MHz) In some of the cases may require: 14800 MHz (e.g. Galactic transients), or 3000 MHz (for long term monitoring of afterglows with steep spectra)
Total Bandwidth (MHz)	1 GHz / polarization for VLBI beams (equivalent of 8 Gbit/s/beam for 2-bit sampling)
Minimum and maximum frequency over the entire range of the setup (MHz)	Central frequency ±512 MHz
Spectral resolution (kHz)	Minimum 500 kHz (external correlator concern)

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Temporal resolution (in seconds)	Standard Nyquist sampling (VLBI data integration time will be 1-2s at the VLBI correlator; these spectral and time resolutions will allow several arcsec FoV for each target)

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (**X**)*	
Central Frequencies (MHz) (including redshift, observatory correction)	same as for the beamformer
Total Bandwidth (MHz)	1 GHz
Minimum and maximum frequency over the entire range of the setup (MHz)	See above
Spectral resolution (kHz)	200 (normal visibilities from the whole array)
Temporal resolution (in seconds)	10s

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	typically 4 (1 VLBI beam for target, 3 beams for calibrators), but up to 8	
Required angular resolution of a tied array beam (arcmin)	N/A	
Total bandwidth for each tied array beam	1 GHz / polarization for VLBI beams (equivalent of 8 Gbit/s/beam for 2-bit sampling per beam)	
Maximum baseline required (km)	4 km core (8 km baselines)	
Primary beam size (sq degrees)	>0.01	
Number of output channels	5 (200 MHz each centred at the centre frequency of the 256MHz standard channels for the VLBI stations)	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel per polarization	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations)	
Required angular resolution (arcmin) (single value or range)	0.03 (200 mas)
Maximum baseline required (km)	150 km
Mapped image size (degrees)	0.05 (20 arcsec)
Required pixel resolution (arcseconds)	0.05 arcsec
Number of output channels	5000 (200 kHz channels over 1 GHz)
Output bandwidth (minimum and maximum frequency - MHz)	1 GHz

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Required rms (Jy per beam) (if polarisation products required define for each)	$3x10^{-7}$ Jy/beam; assuming all telescopes	
Dynamic range within image (if polarisation products required define for each)	300 -- I, 30 -- Q/U/V (for primary target)	
Absolute flux scale calibration	**X**	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (VLBI)	
Required angular resolution (arcmin) (single value or range)	10^{-3} arcsec (0.6-3 mas, depending on obs. frequency, VLBI array config., data weighting)
Mapped image size (degrees)	Up to 5x5 arcsec per beam (typically 1x1 arcsec is sufficient when the source position is known at the sub-arcsecond level)
Number of image channels	1024; eventually averaged down to ~32
Channel width (kHz)	500 kHz => 16-32 MHz
Required rms (Jy per beam per channel) (if polarisation products required define for each)	$1.5x10^{-6}$ Jy/beam. Note this sensitivity is achievable with SKA1-MID plus the EVN (and FAST 500m, QTT 110m) for example. We assumed 81% of SKA1-MID core (inner 4 km) is phased-up, providing a rebaselined SEFD of 5 Jy.
Dynamic range within image per channel (if polarisation products required define for	>50 for primary target ~1000 for calibrators

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each)		
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	We require well established policies on how SKA1-MID will respond to external and internal triggers. In addition, well established policies are needed for arranging ToO/trigger style of observations together with a global SKA-VLBI network.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	Beam-formed data degradation due to shadowing and/or cross-talk should not be underestimated. Will likely need a real-time monitoring system of what telescopes contribute to the beam-formed data. SEFD estimates should accurately reflect the situation when part of the array does not contribute to beam-formed data.
Data products	We indicated above that we need both beam-forming for SKA-VLBI from the core, and simultaneous whole array SKA1-MID interferometer data/products (coarse channelization is fine). The latter will be extremely valuable for total flux density and polarization monitoring of the target, and at the same time for the accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field. (Note for VLBI we do not have primary flux density calibrators, therefore the calibration of the individual telescopes is usually based on measured Tsys, and a-priori assumed telescope gain; having VLBI calibrators with accurately known flux densities at the epoch of observation will help VLBI calibration.) The primary science goal depends highly on the amplitude calibration of all VLBI components, because we want to measure a source size that is a fraction of the beam width.
Description of pipeline	(Near-) real-time imaging pipeline results (of the SKA1-MID interferometer data) after each epoch will be crucial in the decision mechanism on how to proceed with the following epochs.
Quality assessment plan & cadence	The beam-formed products will be streamed (either real-time e-VLBI, or after buffering) to a VLBI correlator centre, that will give feedback on the VLBI data products in either real-time, or ideally within 1-2 days. Cadence of the monitoring observations may depend on both the total flux density evolution and the apparent source size. The cadence will also depend on the transient type and may vary within source types for individual targets. It will range from a few days to a few weeks for certain transients, and a

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	few weeks to a few months (years) for others.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.	'upon completion of scheduling block and pipeline reduction' (approximately 24 hours)

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
1. To get practically thermal noise limited data on the primary target, having ~>1 mJy compact calibrator(s) in the FoV is a basic requirement for this observation, i.e. multiple-beam capability is a must. 2. It is likely that we will not have information on the compactness of mJy sources in the ToO field, therefore we may not know in advance where the additional beams should point to. Various solutions to this include a) pre-selection of flat-spectrum sources in the first hour of the first epoch observation from the SKA1-MID correlation data; these will be best candidates; b) alternatively, if this is real-time e-VLBI, then pre-selection can be based on compactness check from the VLBI data; c) form a large number of beams (>10) and use the data from the small fraction of compact sources. In case of a) and b) one may want to spend more time at the very first epoch (and use less for the rest). 3. One limitation of using large dishes in the VLBI array is that their individual FoV will be significantly smaller than the angular size (FoV) of SKA1-MID beams, i.e. they will have to nod between calibrator and target in a traditional phase-referencing style. If calibrators are to be selected “on-the-fly”, this will mean that the observing schedule will also have to be modified for nodding telescopes. In case of Effelsberg 100m, the calibrator will have to be within an arcminute of the target to avoid nodding. 4. The number of SKA1-MID beams (N) will add to the number of data-streams to be correlated. For N~4-5, this will not be a critical extra load. For more beams (up to 8 in total) a compromise will have to be made in terms of available network bandwidth for electronic transfer of the data to the external VLBI correlator, and also take into account the limited processing resources of the SKA1-MID correlator. 5. The ideal observing frequency is a trade-off between resolution and FoV, that will limit the availability of “in-field” calibrators. Lower part of Band 5 will still work; at higher frequencies using a single SKA1-MID beam and frequent source switching with all telescopes may be the solution. For GW-EM counterparts Band 4 may be the ideal compromise (SKA KSP meeting breakout session discussion in Alderley Edge, April 2019), but currently this is not an operational band in any VLBI arrays. 6. If the observations are real-time e-VLBI, part of the observing time will have to be spent on “clock-searching” and setup before science observations can start.

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7. As mentioned earlier, SKA1-VLBI observations will require coordination with other telescopes. Note since we need long (8000-10000 km) baselines in both N-S and E-W directions, this will constrain the joint visibility of the target and therefore the GST limits when the observations can be carried out.

8. The negative effects of rebaselining is offset by assuming more telescopes in the SKA-VLBI array. The sensitivity gained this way, and the realistic possibility of >5 GHz observations with SKA1-MID (thus better resolution) means that we maintain our original goals of accurate source size determination below ~100 μas level.

REFERENCES

The physical implications of GRB VLBI observations, both in general and in the specific case of GRB 030329 are discussed in the following paper. This also explains how VLBI results are related to radio flux density measurements, light curves at other frequencies, and the overall picture:

Granot, J., van der Horst, A.J., 2014, PASA, 31, 8

Here is an example of a real-time e-VLBI + regular VLBI observation of a transient source in a series of Target of Opportunity monitoring experiments. This demonstrates why nearby calibrators are essential, but also the feasibility of searching suitable calibrators during the first epoch that can be used at subsequent epochs. Ideally, SKA1 would do this at the beginning of the first epoch:

Paragi, Z., van der Horst, A.J., Belloni, T. et al., 2013, MNRAS, 432, 1319

The first VLBI paper on GRB 030329, so far the only afterglow that has been resolved with VLBI. Note this source was 10x brighter (10 mJy at peak) than the typical GRB for which we drafted our science case, i.e. for GRB 030329 type events the SKA-VLBI would do even better. The lower resolution of 3 mas (Band 3) will only provide useful constraints if the target is exceptionally bright (SNR>>50, ξ_{min}<<250 μas), like GRB 030329:

Taylor, G.B., Frail, D., Berger, E., Kulkarni, S.R., 2004, ApJ, 609, L1

First VLBI detections of the EM counterpart to a binary neutron star merger:

Mooley, K.P., Deller, A.T., Gottlieb, O. et al., 2018, Nature, 561, 355

Ghirlanda, G., Salafia, O.,S. Paragi, Z. et al., 2019, Science, 363, 968

For estimating the minimum detectable proper motion, we assumed the source localization accuracy of beamsize/(2xSNR). For the minimum resolvable angular size, we used the approximation $\xi_{min}\sim 0.6\mathrm{x}SNR^{-0.5}$, see:

Martí-Vidal, I., Pérez-Torres, M., Lobanov, A., 2012, A&A, 541, A.135

On the effect of systematic errors on resolution (why SKA-VLBI calibration is important for increasing resolution):

Natarajan, I., Paragi, Z., Zwart, J. et al., 2017, MNRAS, 464, 4306

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1.15 AGN-SUR: A Deep Multi-Frequency VLBI Polarimetric Survey of a Big AGN Sample

PROJECT DETAILS	
Title	**A Deep Multi-Frequency VLBI Polarimetric Survey of a Big AGN Sample**
Principal Investigator	**Iván Agudo**
Co-Authors	**Zsolt Paragi, Michael Garrett, Leonid Gurvits, Paolo Padovani, Marcello Giroletti, Tuomas Savolainen, Antxon Alberdi, Cristina Garcia-Miro, VLBI Science Working Group, Cosmic Magnetism SKA Science Working Group**
Time Request	750h

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	SKA1-MID is selected because of its great potential to perform multiple-frequency VLBI observations. The VLBI capability is an essential ingredient for extragalactic relativistic jet studies in AGN. The possibility to choose high observing frequencies (from ~1 to ≥~20GHz) with SKA-MID is also of extreme interest for AGN jet science.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5+	750h (if observations at four sub-bands [~5, ~8, ~12, ~15 (or ~22 if available)] GHz can be performed simultaneously, otherwise, required observing time increases by a factor of 4), or subarraying could be contemplated.

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	Coordination with other VLBI stations is needed
X	Sub-arrays required	For simultaneous observations at different frequencies in Band 5a and Band 5b

COMMENTS ON OBSERVING STRATEGY
The goal of the science use case outlined here is to scrutinize the finest possible sub-milli-arcsecond (VLBI) angular scales of AGN to characterize the properties of the innermost (and most energetic) regions of their relativistic jets, and their magnetic fields. For that, full-Stokes VLBI observations of a low-flux-limited AGN population in previous SKA deep surveys, at all possible redshifts back from the epoch of re-ionization, will be observed. Three observing frequencies per target is the minimum required to build Faraday rotation

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maps. Here, four frequency sub-bands are considered within the same SKA Band 5+. For SKA1, 2 subarrays will have to be defined for observations using Band 5a and Band 5b, use frequency agility or observe the different bands at different epochs. In the same way, if feasible, the observations at the 4 sub-band would be performed simultaneously for SKA-VLBI by arranging four different external VLBI arrays (each one operating at a different frequency sub-band). Ideally, the four different arrays would be arranged to try to match their resulting angular resolution. Given that AGN jet cores, where the main scientific interest of this science use case is focused, are optically thin at observing frequencies above ~20 GHz (Jorstad et al 2007: http://adsabs.harvard.edu/abs/2007AJ....134..799J) it is more than desirable to shift our set of observing frequencies as high as possible among those available at SKA1-mid. This would allow to observe the targets in the optically thin regime, where we are free from opacity, depolarization and pi/2 polarization angle swaps. If SKA1-mid Band 6 becomes available in the future, this would allow to make this study in optimum conditions to take into account such inconvenient effects. The source sample will be defined from the products of the commensal deep surveys that the Continuum and the Cosmic Magnetism SKA Science Working Groups are designing. Here, we take a section of these surveys with an extension of 100 deg^2 on the sky, but the planned SKA-VLBI observations will be AGN target based. Main products for VLBI imaging come from the SKA (multi-)beam-former. However, imaging products processed in parallel by the SKA correlator must be kept (and delivered by the SRCs) as well for complementary science. This science use case also assumes that all AGN contained in previously observed SKA surveys have already been identified. In particular, analysis of linear polarization observations from such surveys is a unique tool for distinguishing between extragalactic relativistic jets and star forming galaxies. Wide-field very-long-baseline-interferometric observations involving SKA is an additional (complementary) alternative to distinguish between AGN and start forming galaxies up to high redshifts.

POLARISATION PRODUCTS REQUIRED : ***BEAMFORMER*** *(X) or CORRELATOR (__)* *NOTE: Beamformer processes data for VLBI only*			
X	X		Stokes I
X	Y		Stokes Q
			Stokes U
			Stokes V

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (_) or* ***CORRELATOR*** *(X)* *NOTE: Correlator processes data for parallel SKA-alone complementary observations*			
X	XX	**X**	Stokes I
X	YY	**X**	Stokes Q
X	XY	**X**	Stokes U
X	YX	**X**	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
AGN jet studies have been considered a prominent science case for SKA, and have been included in several different chapters of the new SKA Science Book. A number of relevant questions about AGN and extragalactic relativistic jets have remained unanswered while waiting for high sensitivity radio instruments such as SKA to solve them. Analysis of the massive data sets arising from all-sky and deep, full-Stokes SKA surveys will address some of these questions. Moreover, subsequent follow-up studies of these sources at ultra-high VLBI resolutions involving SKA at a broad range of frequencies will allow us, for the first time: i) imaging of a large number of jets throughout cosmic time, back to the epoch of re-ionization; ii) robust relativistic-jet composition studies through unparalleled circular

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polarization sensitivity/purity; iii) an understanding of the radio-loud/radio-quiet dichotomy in extragalactic AGN jets via imaging of thousands of radio weak Seyferts and LINERs; iv) a characterization of the actual properties of relativistic jets, their magnetic field, and their close environment, through deep full Stokes (and Faraday rotation measure) imaging.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Multiple beams from the beamformer, each beam observing one single object, with as many targets as available by the Mid correlator resources (10 VLBI beams for this particular case, up to 6 for 1GHz bandwidth beams).
		Maps through multiple fields of view
	X	Non-imaging pointings (for VLBI beams)
Number of targets	45 sources/deg^2 at a **polarized flux** level greater than ~30 uJy (Rudnick & Owen 2014) = **4500 sources** for 100deg^2	
Positions of targets	Contained on a sky region of area 100deg^2	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ………………………………………..]
	X	NO
Time Critical?		YES [details: ………………………………………..]
	X	NO
Integration time per target (hrs)	**10 minutes**. Image thermal noise estimated to be 6 uJy/beam (1 sigma) using natural weighting for a VLBI array involving the phased SKA-MID core at X-band for 10 minutes integration time per source. For imaging, a minimum of 5 sigma is required, which brings to reliable imaging at the 30 uJy/beam level for 10 minutes integration time. For these computations, an 81% of SKA-MID sensitivity (i.e. the core), and the sensitivities of currently existing VLBI arrays have been considered. For computation of the total observing time per frequency, we assumed 4 SKA-MID beams observing 4 sources simultaneously.	
Average peak flux density (Jy per beam per Hz)	30×10^{-6}Jy/beam (minimum imaged at 5σ level, see above)	
Range of peak flux densities (Jy per beam per Hz)	[10^{-6}Jy, 10Jy] (e.g. Padovani et al. 2007; 2014; Padovani 2011)	
Expected polarised flux density (expressed as % of total)	2% to 5% (Lister et al. 2009; Agudo et al. 2010)	

OBSERVATIONAL SETUP: ***BEAMFORMER*** *(**X**) or CORRELATOR (__)* *NOTE: Beamformer processes data for VLBI*	
Central Frequencies (MHz) (including redshift, observatory correction)	5000, 8400, 12000, 15000, (22000+). 4 observing frequencies per source to have the ability to make reliable Faraday rotation measure maps.
Total Bandwidth (MHz)	500 MHz (corresponding to VLBI data rates of 4 Gbits/s, already tested [EVN Newsletter 36, 2013])

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Minimum and maximum frequency over the entire range of the setup (MHz)	±250 MHz centred on the above mentioned frequencies
Spectral resolution (kHz)	Standard continuum (<100kHz), external correlator concern
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP: *BEAMFORMER (__) or* ***CORRELATOR*** *(X)* *NOTE: Correlator processes data for parallel SKA-alone complementary observations*	
Central Frequencies (MHz) (including redshift, observatory correction)	5000, 8400, 12000, 15000, (22000+).
Total Bandwidth (MHz)	Maximum allowed in each one of the above sub-bands, especially if observing the 4 different bands simultaneously is feasible, only 1 GHz per sub-band, to have enough correlator resources left for beamforming.
Minimum and maximum frequency over the entire range of the setup (MHz)	Determined by the maximum bandwidth and central frequencies.
Spectral resolution (kHz)	Standard continuum (<100kHz)
Temporal resolution (in seconds)	Standard, 1sec

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1 for frequency agility (or 2 for dual band observations)	
Number of tied array beams per subarray	7 VLBI beam for target, 3 beams for calibrators (up to 10, or only 6 beams for 1GHz b/w beams).	
Required angular resolution of a tied array beam (arcmin)	X-band, 3.6 cm and 20 km radius subarray	
Maximum baseline required (km)	40 (for 80% sensitivity)	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~44 µJy in 1 min at X-band ,	
Primary beam size (FWHM, arcmin)	15m antenna X-band	
Total bandwidth for each tied array beam	500 MHz (equivalent to 4 Gbps data rate for 2-bit sampling), or 1 GHz.	
Number of output channels	3 (200 MHz each centred at the centre frequency of the 256MHz standard channels for the VLBI stations)	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	6 uJy/beam (1 sigma)	
Dynamic range (if polarisation products required define for each)	10^4 in Stokes I, 10^5 in polarization	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (VLBI)		
Required angular resolution (arcmin) (single value or range)	~milli-arcsecond scale (even sub-milli-arsecond scale at the highest frequencies). As determined by extended (~10000 km) VLBI array.	
Maximum baseline required (km)	~10000 km	
Mapped image size (degrees)	~ 10 arcsec	
Required pixel resolution (arcseconds)	Arcsecond /sub-milli-arcsecond scale	
Number of output channels	32 per polarization (dual polarisation)	
Output bandwidth (minimum and maximum frequency - MHz)	500 MHz	
Required rms (Jy per beam) (if polarisation products required define for each)	6 uJy/beam (1 sigma)	
Dynamic range within image (if polarisation products required define for each)	10^4 in Stokes I, 10^5 in polarization	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM - single channel of full bandwidth) *NOTE: This section regards to parallel SKA-alone complementary observations only (non-VLBI)*		
Required angular resolution (arcmin) (single value or range)	~1 arcsec → 0.1 arcsec	
Maximum baseline required (km)	Full UV-coverage for SKA-MID	
Mapped image size (degrees)	Standard FoV per pointing	
Required pixel resolution (arcseconds)	~0.1 arcseconds	
Number of output channels	>9200 (Band 5+)	
Output bandwidth (minimum and maximum frequency - MHz)	2x1000 MHz (provided that observing at 2 simultaneous sub-bands is possible, e.g. 5 and 8 GHz and 12 and 15 GHz)	
Required rms (Jy per beam) (if polarisation products required define for each)	Given by integration time at each frequency	
Dynamic range within image (if polarisation products required define for each)	10^6 in Stokes I, 10^5 in polarization	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) *NOTE: This section regards to parallel SKA-alone complementary observations only (non-VLBI) N/A*	
Required angular resolution (arcmin) (single value or range)	
Maximum baseline required (km)	

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Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

DATA ANALYSIS *NOTE: This section regards to parallel SKA-alone complementary observations only (non-VLBI)*	
Procedures required	Multi-frequency synthesis combined with Faraday decomposition pipeline (e.g. Q,U fitting or RM synthesis).
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	
Data products	Main products are VLBI data from the SKA (multi-)beam-former (i.e., standard dual polarisation VLBI formatted data, Tsys & weather curves, and flagging tables). Independent SKA imaging products processed in parallel by the SKA correlator must be kept as well. Fully calibrated I, Q, U and V cubes, as well as Faraday dispersion cubes from polarization multi-frequency synthesis.
Description of pipeline	Should calibrate the data (including polarization specific calibrations), perform RM synthesis, and produce I, Q, U, V & RM image cubes.
Quality assessment plan & cadence	
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	Upon completion of scheduling block and pipeline reduction

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

ISSUES TO BE DETERMINED/RESOLVED
(Here you should include any additional information that needs to be resolved before this science can be carried out)

It is extremely relevant, both for calibration of VLBI observations involving SKA-MID and for wide field VLBI imaging (or multi source VLBI observations, i.e. increasing VLBI survey speed), to have a beamformer with the ability to form as much as possible simultaneous beams. Several tens of beams are desirable. Four beams (1 for target, 3 for high accuracy calibration) is the minimum.

A multi-beamformer for the central core of SKA-MID is the minimum required. Including all baselines of SKA-mid would be ideal. However, if a multi-beam-former using all stations on baselines of ~100km or larger is too difficult to implement, it would still be very useful to have different sub-arrays, each one with its own multi-beam-former, and to send VLBI formatted data streams from each multi-beamformer to an external VLBI correlator. If so, the central core of SKA-MID should obviously form one of the subarrays. This one will dominate the sensitivity of the entire VLBI array, whereas the remaining satellite SKA subarrays will improve the UV coverage.

Data transport from the beam-former to the external VLBI correlator should be discussed since the early stages of the design. This can be done either through fast internet lines for real time VLBI correlation (e-VLBI), or through disk pack shipping. The e-VLBI option will improve the agility of VLBI observations with SKA and decrease the costs of operation of VLBI observations), especially if several beams/subarrays are configured (no data storage needed, no shipping of disk packs). However, e-VLBI will require a broad-band, and stable, internet line to the selected correlator (or at least to the closest broad internet-bandwidth node).

Science ready (SKA alone) polarization accuracy (Q, U & V) should reach levels of at least ~0.1%. In particular, V-Stokes parameters should be as precise as ~ 0.01% for extracting state-of-the-art circular-polarization science of AGN jets.

The source flux estimates presented above are based on low-resolution measurements as compared with VLBI ones. Therefore, flux losses are expected for VLBI beams. This, as well as the effect of the observing frequency on source flux losses needs to be quantified.

It is not clear if simultaneous observing at four different sub-bands of about 2GHz with each, all of them within Band 5+ will be possible. This would help to decrease by a factor of 4 observations like those outlined in this document. Additionally, if SKA1-mid Band 6 becomes available in the future, this would allow to make this study in optimum conditions to account for opacity, depolarization and pi/2 polarization angle swaps.

Conversion between linear to circular polarization will be done similarly as done for ALMA (Marti-Vidal et al. 2016).

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

1.16 BSMBH: Chasing Merged and Merging Supermassive Black Holes

PROJECT DETAILS	
Title	**Chasing Merged and Merging Supermassive Black Holes**
Principal Investigator	**Sonia Antón**
Co-Authors	**Cristina Garcia-Miro, Ian Browne, Chris Skipper, Bruno Coelho, Domingos Barbosa, Bruno Morgado**
Time Request	1000 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	4 hours/target

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-MID array interferometer images, for complementary studies of the target at different angular scales and total flux density and polarization monitoring. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q

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X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
The project is to look for binary supermassive black holes (SMBH), or kicked SMBH, on the milliarcsecond scale using VLBI and optical astrometry to locate AGN displaced from their optical host galaxies. According with hierarchical assembly of galaxies and SMBH models [e.g. 1,2], massive galaxies and BH are built via the merger of smaller units. The associated inflow of gas may trigger AGN activity. In this scenario pairs of AGNs in galaxy mergers are expected of different separations. Only VLBI can probe down to the parsec scale of binary orbits at which point the process of coalescence will start. After coalescence the resulting SMBH may receive a kick which can result on the AGN appearing displaced from it host galaxy [3,4]. Besides providing important tools to understand galaxy evolution, merging or merged SMBH systems are relevant systems for multi-messenger science as potential gravitational wave emission sources. It is therefore of great interest to detect many these systems, as there are very few known systems [eg 5,6]. Different approaches have been used to try to identify such systems, including via spectral-line profiles, variability or offsets between AGN and the host galaxy centre [5,6,7]. We have started searching for offset AGNs by comparing CLASS [8,9] radio positions with SDSS optical ones, and have found several candidates [10]. Being compact the CLASS radio positions, which are accurate to ~20mas, pinpoint the AGN. We propose to analyse some of the 11 000 CLASS objects, taking advantage of the new and astrometric optical data from Gaia (as well as near future synoptic sky survey telescopes), to identify the centre of the host galaxy. Follow up of candidates with SKA-VLBI will have the unique combination of sensitivity and resolution required to detect possible fainter binary companions and/or reveal a disturbed morphology that might occur if an offset AGN is in motion with respect to the host. Preliminary work indicates that there are ~ 250 sources with an angular distance d between the CLASS position and Gaia position (tens of micro-arcsecond accuracy), 150 < d < 1000 mas.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (for VLBI)
Number of targets	~250	
Positions of targets	Retrieved from the Gaia celestial reference frame	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	4 hrs	
Average peak flux density (Jy or Jy per beam)	~10^{-3} Jy/beam	
Range of peak flux densities (Jy or Jy per beam)	~10^{-4} –10^{-2} Jy/beam	
Expected polarised flux density (expressed as % of total)	few %	

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OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	8.4, 15.0 GHz (Band 5b)
Total Bandwidth (MHz)	1 GHz per band
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	Minimum 500 kHz (external correlator)
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	8.4, 15 GHz (Band 5b)
Total Bandwidth (MHz)	1 GHz per observing freq
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	200 (compatible with coarse VLBI visibilities)
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	2 VLBI beams for target (x2 obs. freq.), 6 beams for calibrators (x2 obs. freq.). But only a maximum of 6 beams available for this configuration.	
Required angular resolution of a tied array beam (arcmin)	0.6 arcsec (15 GHz, 2 cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~30 μJy in 1 min at Band 5	
Primary beam size (FWHM, arcmin)	15m antenna 5.3 arcmin (15 GHz, 2cm)	
Total bandwidth for each tied array beam	1 GHz (equivalent to 8 Gbps data rate for 2-bit sampling)	
Number of output channels	5	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-mid local interferometer data using coarse VLBI visibilities)		
Required angular resolution (arcmin) (single value or range)	0.6" (in any case, sub-arcsecond is preferred if possible)	
Maximum baseline required (km)	Whole array	
Mapped image size (degrees)	Standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	1 GHz per observing frequency	
Required rms (Jy per beam) (if polarisation products required define for each)		
Dynamic range within image (if polarisation products required define for each)		
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	
Required angular resolution (arcmin) (single value or range)	~mas In order to try to check for offset btw Gaia/optical position and radio position the astrometry has to be of the order of milliarcsec
Mapped image size (degrees)	~arcsecs
Number of image channels	

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Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)	3x10^{-5} Jy/beam assuming 4km subarray	
Dynamic range within image per channel (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-MID interferometer images from the full array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec or mas level (depending on observing frequency).
Description of pipeline	Standard imaging pipeline for SKA.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	No time critical, same cadence as external correlator.

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Both frequencies can be observed simultaneously. Limited correlator resources allow only 6 VLBI beams for this configuration, but 8 beams at least needed (2 VLBI beams for target, 6 beams for calibrators, for dual frequency observations).

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

1.17 SNe-MID: Inhomogeneous Supernovae studies at low frequencies

PROJECT DETAILS	
Title	**Inhomogeneous Supernovae studies at low frequencies**
Principal Investigator	**Poonam Chandra**
Co-Authors	**Claes-Ingvar Bjornsson, Miguel Perez-Torres, A. J. Nayana, Peter Lundqvist**
Time Request	130.5 hrs

FACILITY		Preconditions
X	SKA1-LOW	Observations to be arranged jointly with a VLBI array.
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
X	SKA1-LOW	90 hrs (including 30% overhead, in 3 years)
X	SKA1-MID Band 1	30 hrs (including 30% overhead, in 3 years)
X	SKA1-MID Band 2	10.5 hrs (including 30% overhead, in 3 years)
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	We need near-simultaneous one observation with SKA-LOW (200-350 MHz subband), SKA1- MID (Band 1) and SKA1-MID (Band 2). We also need another set of near-simultaneous observation around 15 days apart with SKA1-MID (Band 1) and SKA1-MID (Band 2).
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW and SKA1-MID array interferometer images, for complementary studies of the target at different angular scales and total flux density and polarization monitoring. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. Simultaneous observations in Band 1 and 2 could be done using 2 subarrays, 1 subarray with frequency agility. VLBI array could be divided in 2 subarrays for each frequency.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I

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X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
In supernovae (SNe), inhomogeneous emission is caused by variations in the distribution of relativistic electrons and/or the magnetic field within the synchrotron emitting region. This results in a flatter spectral index in the optically thick part due to superposition of varying optical depths. The presence of inhomogeneities would affect several of the conclusions drawn from observations using the standard synchrotron model. The most important is the size of the source thus the derived velocity. If direct velocity estimates are available from other wavelengths, they are generally higher than deduced from radio observations of spatially unresolved SNe with inhomogeneities. This has important consequences in presence of anticipated central engine in some stripped-envelope SNe. However, it is difficult to reveal the presence of inhomogeneities in spatially unresolved sources as the spectrum in the transition region is degenerate. Spatially resolved observations are needed to break this degeneracy and deduce magnetic field and broadness of spectrum caused by inhomogeneities. If inhomogeneities are present, spatially resolved observations via SKA-VLBI will result in higher velocities. To reveal the inhomogeneities in SNe, SKA-VLBI observations, either quasi-simultaneously at two different frequencies within the transition region or at one given frequency at two different times are needed.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
		Non-imaging pointings
Number of targets	Type Ib/c core collapse supernovae within 10 Mpc. 10 targets per year.	
Positions of targets	Individual targets within a single FoV of individual SKA1-LOW station and SKA1-MID dish	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ………………………………………..]
	X	NO
Time Critical?	X	YES [details: observing twice with a gap of ~15 days around SN radio peak]
		NO
Integration time per target (hrs)	For SKA1-LOW: 0.2 mJy/beam level for 60sec integration, 1-sigma. **~ 3 hrs** For SKA1-MID: between 60microJy/beam for band 1 to 30 microJy for band 2, for 60sec integration, 1-sigma. **Band 1 (30 minutes x twice), Band 2 (10 minutes x twice)**	
Average peak flux density (Jy or Jy per beam)	200 μJy	
Range of peak flux densities (Jy or Jy per beam)	0.1 mJy - 2 mJy	
Expected polarised flux density (expressed as % of total)	<1%	

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OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW (200-350 MHz) SKA1-MID band 1 and 2 centres
Total Bandwidth (MHz)	150 MHz for LOW 700 MHz for band 1 (whole band) 810 MHz for band 2 (whole band).
Minimum and maximum frequency over the entire range of the setup (MHz)	200-350MHz 0.35-1.05 GHz 0.95-1.76 GHz
Spectral resolution (kHz)	Minimum 500 kHz (external correlator concern)
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-LOW (200-350 MHz)
Total Bandwidth (MHz)	150 MHz for LOW 700 MHz for Band 1 (whole band) 810 MHz for Band 2 (whole band)
Minimum and maximum frequency over the entire range of the setup (MHz)	200-350MHz 0.35-1.05 GHz 0.95-1.76 GHz
Spectral resolution (kHz)	Standard for Low correlator Standard for Mid correlator
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS	
Number of subarrays	1 (2 for simultaneous observations)
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-LOW station or SKA1-MID dish, at least 4 (1 target + 3 calibrators)
Required angular resolution of a tied array beam (arcmin)	178/25.5 arcsec (50/350MHz, 600/86cm and 4 km radius subarray) 9/5.4 arcsec (900/1600MHz, 30/18cm and 4 km radius subarray)
Maximum baseline required (km)	8
Required baseline sensitivity	Between SKA1-LOW VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min Between SKA1-MID VLBI beam and a 100m-class dish is ~ 70/30 microJy in 1 min for Band 1/2.
Primary beam size (FWHM, arcmin)	40m stations 10/1.4deg (50/350MHz, 600/86 cm) 15m dishes 1.3/0.8deg (900/1600MHz, 30/18 cm))
Total bandwidth for each tied array beam	For LOW 150 MHz (equivalent to 1.2 Gbps data rate for 2-bit sampling per VLBI beam) For MID 800 MHz (equivalent to 6.25 Gbps data rate for 2-bit sampling per VLBI beam)
Number of output channels	4
Output bandwidth (minimum and maximum frequency - MHz)	64 MHz per channel for LOW 200 MHz per channel for MID

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Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-LOW/MID local interferometer data)		
Required angular resolution (arcmin) (single value or range)	For LOW several arcsec for highest frequencies, up to tenths of arcsec for the lowest frequencies For MID 0.2 arcsec for highest frequencies, up to 1 arcsec for the lowest frequencies	
Maximum baseline required (km)	Full LOW/MID array	
Mapped image size (degrees)	Standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	150 MHz bandwidth 700/800 MHz bandwidth for Band 1/2	
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-LOW continuum sensitivities (from 11×10^{-6} to 163×10^{-6} Jy/beam for 1h integration) Typical SKA1-MID continuum sensitivities for Band 1/2 (from 1.7×10^{-6} to 15.6×10^{-6} Jy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A	
Required angular resolution (arcmin) (single value or range)	
Maximum baseline required (km)	
Mapped image size (degrees)	

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

Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	25 mas to 0.2 arcsec depending on observing frequency for LOW ~mas for MID (depending on obs. frequency, VLBI array config., data weighting)	
Mapped image size (degrees)	Up to 5x5 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1-LOW VLBI beam and a 100m-class dish is ~0.2 mJy in 1 min Between SKA1-MID VLBI beam and a 100m-class dish is ~ 70/30 microJy in 1 min for Band 1/2.	
Dynamic range within image (if polarisation products required define for each)	>50 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-LOW/MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-LOW/MID interferometer images from the full arrays.

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	Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec or mas level (depending on observing frequency).
Description of pipeline	Standard imaging pipeline for SKA1-LOW/MID, standard VLBI pipelines for SKA-VLBI data.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	No time critical, similar cadence as external correlator.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
To get practically thermal noise limited data on the primary target, having ~>1 mJy compact calibrator(s) in the FoV is a basic requirement for this observation, ie. multiple-beam capability is a must (1 target + 3 calibrators). VLBI Low frequency array is currently in development. Fringes between MWA and uGMRT were demonstrated recently (Kirsten et al. 2016). Few telescopes will have low frequency capability (e.g. uGMRT, FAST, Miyun, Past and Tianlai, etc.), with limited uv coverage, image reconstruction algorithms for low frequencies will need to be improved.

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

1.18 GLOB-ASTR: Massive densification of the radio reference frame with SKA-VLBI: searching for Gaia counterparts

PROJECT DETAILS	
Title	**Massive densification of the radio reference frame with SKA-VLBI: searching for Gaia counterparts**
Principal Investigator	**Patrick Charlot (CNRS/Univ. Bordeaux)**
Co-Authors	**Cristina Garcia-Miro (SKAO), Tao An (Shanghai Astronomical Observatory), Bob Campbell (JIVE), Paco Colomer (JIVE), Alet de Witt (Hartebeesthoek Radio Astronomy Observatory), Phil Edwards (CSIRO), Sébastien Lambert (Paris Observatory)**
Time Request	5000 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with VLBI arrays.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	5000

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
X	Commensal	Gaia sources in the field
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner km core

COMMENTS ON OBSERVING STRATEGY
While the project will rely on beamformed data for SKA-VLBI for its primary astrometric goal, it will also take advantage of the simultaneous SKA1-MID interferometer images produced from the same subarray. The latter will be used for complementary studies of the targets at lower angular resolution and measurement of total flux density and polarization. It is anticipated that about 250 targets could be measured per day (24h sessions) with 3 to 5 1-min long scans (pointings) on every target. Sub-netting may be considered within the VLBI array, i.e. only a subset of the antennas would be observing at a given time, to optimize observing time and avoid losses when antennas are slewing from one target to the next. To correct for the dispersive ionospheric effects, we are interested in observing two separated frequency windows in Band 5, one at the lower end of Band 5a, the other at the

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higher end of Band 5b. As these two bands cannot be observed simultaneously, frequency agility will be required. As an alternative to frequency agility, two different subarrays could be configured (one for Band 5a and the other for Band 5b) that would observe simultaneously. In that case, the two sub-arrays may also alternate observations between the two bands to assess and correct for instrumental effects. A third alternative, also to be explored, would be to observe only the lower end and upper end of Band 5b on the assumption that the separation between the two frequencies is sufficient for ionospheric effect correction. Commensal observing will be possible whenever there is a Gaia source in the SKA1-MID field of view and processing resources are available to provide two VLBI beams.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q
X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
The purpose of the project is to conduct a survey of 50,000 extragalactic sources (active galactic nuclei) selected randomly from the Gaia celestial reference frame using SKA in VLBI mode and to measure their astrometric positions with sub-milliarcsecond accuracy. The sample is about 10% of the Gaia celestial reference frame which comprises 500,000 objects (Mignard et al. 2018). The scientific goals are: (i) to assess the detection rate of the optical Gaia sources when observed in radio with high sensitivity, (ii) to densify the current VLBI celestial reference frame, i.e. the ICRF3 which comprises 5000 sources (Charlot et al. 2019), by an order of magnitude, and (iii) to assess the level of coincidence between optical and radio positions on a statistical basis and infer geometric properties of the underling active galactic nuclei. The foreseen VLBI networks that could observe jointly with SKA are the EVN (European VLBI Network), including telescopes in Asia, the developing AVN (African VLBI Network), and the Australian LBA (Long Baseline Array). Correlation would be carried out at JIVE or at other institutions (e.g. CSIRO, Shanghai Astronomical Observatory).

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	50,000	
Positions of targets	Retrieved from the Gaia celestial reference frame	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………….]
	X	NO
Time Critical?		YES [details: ……………………………………….]
	X	NO
Integration time per target (hrs)	1 min	

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Average peak flux density (Jy or Jy per beam)	~10^{-3} Jy/beam
Range of peak flux densities (Jy or Jy per beam)	~10^{-4} –10^{-1} Jy/beam
Expected polarised flux density (expressed as % of total)	A few %

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	5.1 GHz and 14.8 GHz (if observing both Band 5a and Band 5b) or 8.8 GHz and 14.8 GHz (if observing only Band 5b)
Total Bandwidth (MHz)	2 GHz (1+1 GHz)
Minimum and maximum frequency over the entire range of the setup (MHz)	4.6 GHz and 15.3 GHz (if observing both Band 5a and Band 5b) or 8.3 GHz and 15.3 GHz (if observing only Band 5b)
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	5.1 GHz and 14.8 GHz (if observing both Band 5a and Band 5b) or 8.8 GHz and 14.8 GHz (if observing only Band 5b)
Total Bandwidth (MHz)	2 GHz (1+1 GHz)
Minimum and maximum frequency over the entire range of the setup (MHz)	4.6 GHz and 15.3 GHz (if observing both Band 5a and Band 5b) or 8.3 GHz and 15.3 GHz (if observing only Band 5b)
Spectral resolution (kHz)	200 (using coarse VLBI visibilities)
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS	
Number of subarrays	1 for frequency agility or single band (or 2 for dual-band observations)
Number of tied-array beams per subarray	2 VLBI beams
Required angular resolution of a tied array beam (arcmin)	0.6" at 15 GHz (assuming a 4-km radius subarray)
Maximum baseline required (km)	8
Required baseline sensitivity	between SKA1 VLBI beam and a 30m-class dish is ~100 μJy in 1 min
Primary beam size (FWHM, arcmin)	5.3 arcmin at 15 GHz for a 15m antenna
Total bandwidth for each tied-array beam	1 GHz (equivalent to 8 Gbps data rate for 2-bit sampling)
Number of output channels	5 (200 MHz each centred at the centre frequency of the 256 MHz standard channels of the VLBI stations)
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel

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Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-mid local interferometer data using coarse VLBI visibilities)		
Required angular resolution (arcmin) (single value or range)	0.6" (in any case, sub-arcsecond is preferred if possible)	
Maximum baseline required (km)	8 km	
Mapped image size (degrees)	standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	1 GHz	
Required rms (Jy per beam) (if polarisation products required define for each)	$3x10^{-7}$ Jy/beam (assuming a 4 km radius subarray)	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A	
Required angular resolution (arcmin) (single value or range)	
Maximum baseline required (km)	
Mapped image size (degrees)	
Required pixel resolution (arcseconds)	
Number of image channels	
Channel width (kHz)	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	
Dynamic range within image per channel	

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(if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	N/A (only astrometric products)	
Required angular resolution (arcmin) (single value or range)		
Mapped image size (degrees)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-MID interferometer images from the same subarray. Final SKA-VLBI data products produced by the PI will be astrometric products (source positions with milliarcsecond accuracy and flux densities).
Description of pipeline	Standard imaging pipeline for SKA, astrometric pipelines for SKA-VLBI data.
Quality assessment plan & cadence	First observe 1000 sources selected randomly from the Gaia celestial frame to assess detection rates. Depending on the results, adjust observing strategy if necessary. Technical details to be assessed also during this first round.
Latency (Desired time lag between	VLBI beam voltages need to be provided from the

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observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	SKA VLBI terminal to the external correlator in a timely manner, before correlation takes place (several weeks after the observation took place). For individual sources observations in commensal mode with other observing projects, e-VLBI real-time transfer mode could be use as the total amount of data will be low, but this is not mandatory.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Following issues will need to be explored or resolved for present science case: • Commensal observing details. • Frequency agility details between Band 5a and Band 5b. • Observations with different subarrays and instrumental calibration. • Ionospheric corrections using just Band 5b (as opposed to using both Band 5a and Band 5b) • Broad-band approach to solve for phase and ionosphere corrections simultaneously.

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Charlot, P. 2010, *Precision Astrometry: from VLBI to Gaia and SKA*, The Square Kilometre Array: Paving the way for the new 21st century radio astronomy paradigm, Eds. D. Barbosa, S. Anton, L. Gurvits and D. Maia, Astrophysics and Space Science Proceedings, Springer, p. 85-95 Charlot et al. 2019, *The Third Realization of the International Celestial Reference Frame*, A&A, in preparation Mignard et al. 2018, *Gaia Data Release 2 – The celestial reference frame (Gaia-CRF2)*, A&A, 616, A14

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1.19 CONT-ASTR: High precision astrometry of continuum sources in star forming regions

PROJECT DETAILS	
Title	**High precision astrometry of continuum sources in star forming regions**
Principal Investigator	**Sergio Dzib**
Co-Authors	**Andreas Brunthaler, Gisela Ortiz, Laurent Loinard**
Time Request	100 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	100% of SKA1-mid collecting area phased up, simultaneous availability of LBA (Long Baseline Array), AVN (African VLBI Network) and EVN (European VLBI Network) antennas.
	SKA1-SURVEY	

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	100

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	4 epochs over a 1-2 year period close to the date where the parallax signature is largest (March and September)
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	Simultaneous availability of Long Baseline Array (Australia), African VLBI Network and European VLBI Network antennas with 6.7 GHz receiver capability
	Sub-arrays required	

COMMENTS ON OBSERVING STRATEGY
Scheduling commensal with VLBI network. The minimum required is 4 phased beams, 3 for calibrators, 1 for target. For most fields, several dozens beams could be utilized if available (maximum number of VLBI beams is 52 with 200 MHz b/w each per pol, per subarray using VLBI coarse visibilities for Imaging). Observe International Celestial Reference Frame (ICRF) sources for tropospheric calibration

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of the VLBI array.

Primary output is VLBI-formatted beamformed data. It is desirable to collect SKA1-MID continuum imaging data in parallel for comparison with the VLBI data.

Sources need to be observed at 4 epochs spread over 18-24 months at times when the parallax signature is greatest.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or CORRELATOR (_)*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (__) or CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Star forming regions contain tens to hundreds of low-mass young stellar objects (YSOs) with non-thermal radio emission (e.g., Dzib et al. 2013, Forbrich et al. 2016). VLBI observations of these kind of YSOs have been used to measure their trigonometric parallax and proper motions to distances around 1 kpc (Dzib et al. 2016). They have also been used to study the 3D distribution in complex nearby star forming regions (e.g. Ortiz-Leon et al. 2017; Galli et al. 2018). However, these studies are restricted to the strongest YSOs with the strongest radio emission (>150 uJy), a situation that the SKA will change with its extraordinary sensitivity. Loinard et al. (2015) show that there would exist an in beam calibrator with flux level above 500uJy at the observed frequency. In this case, to achieve an astrometric accuracy of 10uas with the SKA1-MID one hour of on-source time is needed. For the astrometric study of 260 YSOs in 20 observed primary fields (13 target + 3 calibrator beams per primary field) and four epochs in two years (accommodated in the months were the maximum parallax separation occur) we would need 100 hour of telescope time (including overheads).

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	Several star forming regions covering a range of Galactic longitudes and LSR velocities.	
Positions of targets	Galactic plane covering full range of longitudes visible from the southern hemisphere.	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………….]
	X	NO
Time Critical?	X	YES [details: Observations required near the equinoxes to maximise the amplitude of the parallax signal. Time window is of the order of 4 weeks]
		NO
Integration time per target	60 minutes per field per epoch.	

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(hrs)	
Average peak flux density (Jy per beam)	100 uJy per beam
Range of peak flux densities (Jy per beam)	40-300 uJy per beam
Expected polarised flux density (expressed as % of total)	Small, few percent maximum

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Band 5 (6 GHz)
Total Bandwidth (MHz)	500 MHz (dual polarization)
Minimum and maximum frequency over the entire range of the setup (MHz)	Exact values not important, but will utilise as large a spread in bandwidth as can be accommodated by the receiver/backend hardware to obtain optimal calibration of the zenith tropospheric delay
Spectral resolution (kHz)	(external correlator concern)
Temporal resolution ('dump' time in s or 'standard')	Standard Nyquist sampling
OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Band 5 (6 GHz)
Total Bandwidth (MHz)	500 MHz (dual polarization)
Minimum and maximum frequency over the entire range of the setup (MHz)	Exact values not important, but will utilise as large a spread in bandwidth as can be accommodated by the receiver/backend hardware to obtain optimal calibration of the zenith tropospheric delay
Spectral resolution (kHz)	standard continuum for full 500 MHz band (200 kHz with VLBI visibilities)
Temporal resolution ('dump' time in s or 'standard')	Standard, 1s

NON-IMAGING SPECIFIC CONSIDERATIONS	
Number of subarrays	1 (Full array)
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-MID dish, up to 16 VLBI beams per subarray (e.g. 13 targets, 3 calibrators)
Required angular resolution of a tied array beam (arcmin)	0.1 arcseconds or larger
Maximum baseline required (km)	N/A, phasing of full array
Required baseline sensitivity	~20 □Jy/beam (SKA1-mid to 25m class antenna).
Primary beam size (sq degrees)	0.015 square deg (SKA1-mid 6.7 GHz FoV)
Total bandwidth for each tied array beam	500 MHz (4 Gbps for 2-bit sampling, per VLBI beam)
Number of output channels	3
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz

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Required rms (Jy) (if polarisation products required define for each)	8 µJy beam^{-1}	
Dynamic range (if polarisation products required define for each)	60:1	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-mid local interferometer data using coarse VLBI visibilities)		
Required angular resolution (arcmin) (single value or range)	0.08 arcsec	
Maximum baseline required (km)	N/A, full array	
Mapped image size (degrees)	0.015 square deg (SKA1-mid 6.7 GHz FoV)	
Required pixel resolution (arcseconds)	Standard for VLBI visibilities	
Number of output channels	1024	
Required rms (Jy per beam) (if polarisation products required define for each)	100 µJy beam^{-1}	
Dynamic range within image (if polarisation products required define for each)	60:1	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (VLBI)		
Required angular resolution (arcmin) (single value or range)	1.2 milliarcseconds (8000 km VLBI baselines at 6.7 GHz)	
Single Field-Of-View or mapped image size (degrees)	1 arcsecond for each phased-array beam (one for maser sources), remaining on background calibrator targets within FoV	
Number of image channels	1024	
Channel width (kHz)	200 kHz	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	8 μJy $beam^{-1}$	
Dynamic range within image per channel (if polarisation products required define for each)	60:1	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Correlator: standard Beamformer: Will use standard VLBI techniques
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	Flag data for antennas off-source
Data products	Correlator: standard Beamformer: VDIF baseband data (includes metadata eg time stamps. Description of VDIF standard is available at http://vlbi.org/vdif/)
Description of pipeline	Correlator: standard Beamformer: Streaming of data to appropriate VLBI correlator. Data rate for phased SKA-mid is 4 Gbps per beam, although project could utilise higher data rates, if they were available. Data from outstations (LBA, AVN etc) also to be streamed to VLBI correlator site.
Quality assessment plan & cadence	Records of delays, phases, fringe rates
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	Upon completion of scheduling block and pipeline reduction.

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Requirements for this project are very similar to those for "Parallax measurements of southern hemisphere pulsars". Specifically, an accurate frequency standard (e.g. hydrogen maser) at each VLBI site. For in-beam calibration it is desirable if as many VLBI sites as possible have the same FoV as the SKA1-mid antennas, this technique is more complicated for a heterogeneous VLBI array. For heterogeneous arrays with some larger diameter (smaller FoV) antennas in-beam phase calibration will only be possible for a subset of sources where suitable calibrators are within the FoV of the larger antennas. CSP Mid correlator processing resources are limited, the number of VLBI beams (e.g. a maximum of 16 available with 500 MHz b/w, or 52 beams with 200 MHz b/w) will have to be chosen depending on the characteristics of the target field, trading with bandwidth.

REFERENCES

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1.20 EXOPL-MID: Radio emission from massive exoplanets as a powerful tool to study their properties and evolution

PROJECT DETAILS	
Title	**Radio emission from massive exoplanets as a powerful tool to study their properties and evolution**
Principal Investigator	**Marcin Gawroński**
Co-Authors	**Krzysztof Katarzyński**
Time Request	300 hrs

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
X	SKA1-MID Band 1	~150 hrs (50 stars * 3hrs)
X	SKA1-MID Band 2	~150 hrs (50 stars * 3hrs)
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW array interferometer continuum images, for complementary studies of the target -total flux density integration-. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ()*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q
X	XY	X	Stokes U

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X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
The possibility of the detection of radio emission produced by extrasolar planets was already suggested by several authors (see Grießmeier+2011 for a review). However, in all cases the predictions were postulating an emission limited to the MHz frequency range. Such emission may originate when the stellar wind collides with the magnetosphere of a massive object. Despite many trials such emission was not discovered so far (e.g. Lynch+2017, O'Gorman+2018). In the Solar system such radiation is observed from kHz to MHz frequencies (below 40 MHz in the case of Jupiter). The maximum frequency of this radiation is simply the cyclotron frequency, that depends only on the magnetic field strength. Therefore, objects with significantly higher magnetic field may extend their emission even to the GHz frequencies. Theoretical models predict such relatively large (B > 10^3 G) magnetic fields in young massive planets (M > 8 M_Jup) and brown dwarfs (e.g. Burrows+1997). These predictions were recently confirmed by the observations of radio emission at GHz range from brown dwarfs (e.g. McLean+2012). We propose observations of a selected sample of young, massive main-sequence stars at L-band using SKA1-MID Bands 1 & 2. Such stars are always relatively young (age < 1Gy) and possible companions of these object must also be young and magnetically strong. Under reasonable assumptions it can be shown that the expected fluxes could exceed ~30μJy for low-mass brown dwarfs located at distances similar to Jupiter's (see Katarzyński+2016 for details). The combined SKA-VLBI network will allow to distinguish putative radio emission from the position of the host star, and two band observations will be important in the estimation of magnetic field properties of possible massive exoplanets.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (for VLBI)
Number of targets	Young massive planets and brown dwarfs, ~50 targets (including known massive exoplanets)	
Positions of targets	Position, proper motion and parallax estimations from Gaia catalogs.	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	3hrs/target/band	
Average peak flux density (Jy or Jy per beam)	~30-100 μJy/beam	
Range of peak flux densities (Jy or Jy per beam)	~30-100 μJy/beam	
Expected polarised flux density (expressed as % of total)	up to ~100% - depends on the geometry of the emitting region/regions.	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID bands 1,2

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Total Bandwidth (MHz)	500 MHz each band (4 Gbps for 2-bit sampling, per VLBI beam per band)
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	external correlator concern
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID bands 1,2
Total Bandwidth (MHz)	500 MHz for continuum each band
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	Standard for Mid correlator (13.44 kHz for all bands), coarse visibilities 200 kHz
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1 (2 for dual frequency observations)	
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-MID dish, up to 14 VLBI beams per subarray (11 targets, 3 calibrators)	
Required angular resolution of a tied array beam (arcmin)	5.4 arcsec (21 cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~38 μJy in 1 min, at L-band with 500 MHz b/w	
Primary beam size (FWHM, arcmin)	15m antenna 0.9deg (21cm)	
Total bandwidth for each tied array beam	500 MHz (equivalent to 4 Gbps data rate for 2-bit sampling, per band)	
Number of output channels	2 or 3	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel (centred at the centre frequency of the 256 MHz standard channels for the VLBI stations)	
Required rms (Jy) (if polarisation products required define for each)	~10 μJy/beam in order to have ~5σ detection	
Dynamic range (if polarisation products required define for each)	5-20	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-MID local interferometer data)	
Required angular resolution (arcmin) (single value or range)	0.4" (in any case, sub-arcsecond is preferred if possible)

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Maximum baseline required (km)	Whole array	
Mapped image size (degrees)	standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	500 MHz bandwidth	
Required rms (Jy per beam) (if polarisation products required define for each)	~10 µJy/beam	
Dynamic range within image (if polarisation products required define for each)	>5 for primary target	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	~mas (8000 km VLBI baselines)	
Mapped image size (degrees)	Up to 5x5 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~40-80 Jy/beam mean level for band 1 and 2, for 60sec integration, 1-sigma.	
Dynamic range within image (if polarisation products required define for each)	>10 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
	X	5%

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		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data produced from different subarrays for SKA-VLBI to obtain high frequency resolution VLBI visibilities, and simultaneous SKA1-MID interferometer images from the whole array.
Description of pipeline	Standard imaging pipeline for SKA1-MID Standard imaging pipeline for SKA-VLBI data
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	No time critical, similar cadence as for the external VLBI correlator (e.g. 1-2 months).

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Accuracy in the targets position, proper motion and parallax may limit the size of the phase-up subarray, compromising sensitivity. VLBI networks are weak in Band 1 (UHF) but sensitive antennas have that capability (including Eff, Jb-1, uGMRT, FAST, etc.).

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

1.21 SCINT-MID: Pulsar Scintillometry with SKA1-MID

PROJECT DETAILS	
Title	**Pulsar Scintillometry with SKA1-MID**
Principal Investigator	**Franz Kirsten**
Co-Authors	**Dana Simard, Robert Main, Dan Stinebring, Ue-Li Pen, Jean-Pierre Macquart, Olaf Wucknitz**
Time Request	1000

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
X	SKA1-MID Band 1	1000
X	SKA1-MID Band 2	1000
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	1000

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
X	Commensal	Simultaneous pulsar timing processor in order to refine the target pulsar(s) ephemeris.
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	3 subarrays, one for each frequency band, dividing the 4 km inner core. Subarrays with same resolution.

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous SKA1-MID subarrays interferometer images, for accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. This project will also make use of the multi-beam capability for phase referencing between different calibrators to the target. To trace scintillation and how it evolves with frequency, it is needed to cover as large observing bandwidth as possible. One possibility is to observe simultaneously at several bands using subarrays (e.g. 3 subarrays for bands 1, 2 and 5). The VLBI network will either have to observe broadband (e.g future Brand-EVN receiver) or define subarrays for each frequency (e.g. similar approach as the one adopted for

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RadioAstron ground-based co-observations). However, even if only parts of the whole available bandwidth of SKA1-Mid are covered by external stations, we would be able to use the autocorrelations to interpolate between the parts of the band with and without frequency overlap at external stations.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
We would like to use SKA-VLBI on pulsars to understand scattering in the ISM and, at the same time, perform extreme precision astrometry. One aspect of this is to trace scintillation across a large bandwidth. This will give us more insight on the physics of turbulence in the ISM; i.e. Kolmogorov turbulence (e.g. Walker et al. 2004, Cordes et al. 2006) vs. current sheet models (e.g. Pen & Levin 2014, Simard & Pen 2018). Doing this with VLBI will allow us to map out the speckle image, measure its size and predict the relative location of speckles at different frequencies -- a concrete test of the corrugated sheet model. A further aspect of pulsar scintillation is that one can resolve pulsar magnetospheres to constrain models of pulsar emission. We need VLBI to a) measure an accurate distance to the pulsar which we then use to b) measure an accurate distance to the scattering screen (Ds, Brisken et al. 2010). Once we know Ds we can use the speckles on the scattering screen as stations in an interferometer that are several AU apart, i.e. have a tremendous resolving power. This can then be applied to measure the physical size of the emission region of a pulsar which places constraints on the emission height (Pen et al. 2014). Furthermore, for binary pulsars scintillation gives us access to the sense of the inclination of the orbits, and thus pulsar masses (e.g. Rickett 2014, Reardon 2019). This only works on very bright targets; with SKA we could do this on many more sources that are much fainter.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	100 - 500	
Positions of targets	Individual targets within a single FoV of individual SKA1-MID dish	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ………………………………………..]
	X	NO
Time Critical?		YES [details: ………………………………………..]
	X	NO
Integration time per target (hrs)	2 hrs per pulsar to collect enough scintils. (~100 □Jy/beam mean level amongst different MID bands, for	

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	60sec integration, 1-sigma, and a 100m class remote telescope)
Average peak flux density (Jy or Jy per beam)	50 mJy/beam
Range of peak flux densities (Jy or Jy per beam)	1 – 1000 mJy/beam
Expected polarised flux density (expressed as % of total)	10-100 %

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID bands 1,2, 5 centres
Total Bandwidth (MHz)	500 MHz each band (4 Gbps for 2-bit sampling, per VLBI beam per band)
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	High-resolution visibilities ~2s, several kHz (external correlator concern)
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID bands 1,2, 5 centres
Total Bandwidth (MHz)	500 MHz each band
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	Standard for Mid correlator, 13.44 kHz for all bands
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS	
Number of subarrays	3
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-MID dish, up to 4 VLBI beams per subarray (1 target, 3 calibrators)
Required angular resolution of a tied array beam (arcmin)	0.6 arcsec (15 GHz, 2 cm and 4 km radius subarray)
Maximum baseline required (km)	8
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~100 □Jy/beam mean level amongst different MID bands, for 60sec integration, 1-sigma
Primary beam size (FWHM, arcmin)	15m antenna 5.3 arcmin (15 GHz, 2cm)
Total bandwidth for each tied array beam	500 MHz (equivalent to 4 Gbps data rate for 2-bit sampling, per band)
Number of output channels	2 or 3
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel (centred at the centre frequency of the 256 MHz standard channels for the VLBI stations)
Required rms (Jy) (if polarisation products required define for each)	N/A

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Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
		5%
		10%
	X	20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-MID local interferometer data)		
Required angular resolution (arcmin) (single value or range)	0.6" (in any case, sub-arcsecond is preferred if possible)	
Maximum baseline required (km)	whole array	
Mapped image size (degrees)	standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	500 MHz bandwidth	
Required rms (Jy per beam) (if polarisation products required define for each)	$3x10^{-7}$ Jy/beam; assuming 4km subarray	
Dynamic range within image (if polarisation products required define for each)	300 – I, 30 – Q/U/V	
Absolute flux scale calibration		1-3%
		5%
		10%
	X	20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	~mas (8000 km VLBI baselines)	
Mapped image size (degrees)	Up to 5x5 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~100 □Jy/beam mean level amongst different MID bands, for 60sec integration, 1-sigma.	
Dynamic range within image (if polarisation products required define for each)	>50 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
		5%
		10%
	X	20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data produced from different subarrays for SKA-VLBI to obtain high frequency resolution VLBI visibilities, and simultaneous SKA1-MID interferometer images from the same subarrays.
Description of pipeline	Standard imaging pipeline for SKA1-MID Scintillation analysis pipelines for SKA-VLBI data
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.)	No time critical, similar cadence as for the external VLBI correlator (e.g. 1-2 months).

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
The VLBI network will either have to observe broadband (e.g future Brand-EVN receiver 1.5-15.5 GHz first prototype for EVN antennas will be ready by 2020) or define subarrays for each frequency (e.g. similar approach as the one adopted for RadioAstron ground-based co-observations). Compatibility between 200 MHz channels and standard VLBI channels (base 2).

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

1.22 SGRAVL: Testing models for galaxy formation and dark matter, and investigating the high redshift Universe with strong gravitational lensing (VLBI)

PROJECT DETAILS	
Title	**Testing models for galaxy formation and dark matter, and investigating the high redshift Universe with strong gravitational lensing (VLBI)**
Principal Investigator	**J. P. McKean**
Co-Authors	**R. Deane, C. D. Fassnacht, L. V. E. Koopmans, N. Jackson, P. J. Marshall, R. B. Metcalf, M. Pandey-Pommier, M. Rybak, S. Serjeant, C. Spingola, S. Vegetti**
Time Request	2000 hrs: 1250 hours (commensal) in Band 2 + 750 hours (targeted) in Band 5

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a global VLBI array

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
X	SKA1-MID Band 2	1250 hours
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	750 hours

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
X	Normal	Targeted observations in Band 5
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
X	Commensal	The project could be carried out in combination with the SKA1-MID surveys thanks to simultaneous correlation and beamforming of the data (for Band 2)
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	inner 4 km core

COMMENTS ON OBSERVING STRATEGY
The observing strategy is for a dedicated gravitational lensing survey, although the same strategy can be used for any large area survey being carried out with SKA-MID in Band 2. In this case, wide-field VLBI of the survey data would be carried out commensally. The proposed pilot survey will be for a 7500 sq. deg. region of sky (the Euclid southern field) to a depth of 6 uJy beam^{-1}. The resolution of the SKA-MID array is 0.3 to 0.5 arcsec (for uniform weighting), which will be improved to between 1 and 200 mas. The survey data will first be taken with the SKA-MID array, forming images at 0.3 arcsec resolution for source

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finding. The SKA-MID would then phased up and multiple correlations (averaged datasets) would be made at the location of the sources. This functionality will provide a clean method for selecting lensed objects. Follow-up observations of confirmed lenses at Band 2, 5a and 5b will be needed for many of the science goals of the survey. For high redshift objects detected by the SKA1-MID Band 2 survey, produce commensally beamformed data in Band 5 for participation in simultaneous VLBI observations.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Strong gravitational lenses provide an important tool to measure masses in the distant Universe, thus testing models for galaxy formation and dark matter; to investigate structure at the Epoch of Reionization; and to measure the Hubble constant and possibly *w* as a function of redshift. However, the limiting factor in all of these studies has been the currently small samples of known gravitational lenses ($\sim 10^2$). 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 to $\sim 10^5$ [1]. The SKA-MID pilot survey will detect > 10^3 gravitational lenses with the following science goals. 1) Constrain models for the (very) high redshift radio source population – this requires uniform sensitivity and wide-fields of view at >0.3 arcsec resolution [1]. 2) Test models for dark matter through detailed lens modelling – this requires both sensitive and mas-scale angular resolution imaging [2]. 3) Investigate galaxy and black hole evolution through detection of central lensed images – this requires sensitivity, high dynamic range and mas-scale angular resolution [3]. 4) Test plasma lensing models to investigate the ionized medium of lens galaxies – this requires large bandwidth observations at mas-scale angular resolution [4]. 5) Test AGN feedback and star formation at high redshift by combining synchrotron and free-free emission, with resolved CO (1-0) molecular gas imaging – this requires mas-scale angular resolution [5]. 6) Test jet dynamics / binary black hole models in the early Universe through resolved jet kinematics – this requires mas-scale angular resolution and multiple observations over time [6].

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7) Test cosmological models through maser kinematics and dynamical time-delays of radio jets -- this requires mas-scale angular resolution and multiple observations over time [7].

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	10^6 for pilot survey	
Positions of targets	Gravitational lenses accessible to SKA1-MID	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	3 mins for pilot survey at Band 2 < 8 hours per target for Band 5 follow-up	
Average peak flux density (Jy or Jy per beam)	>50μJy/beam, the image-separation distribution has a range between 0.1 and 5 arcsec (effective field of view needed).	
Range of peak flux densities (Jy or Jy per beam)	1-1000 μJy/beam	
Expected polarised flux density (expressed as % of total)	A few %	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Band 5
Total Bandwidth (MHz)	1 to 4 GHz (multiple observations)
Minimum and maximum frequency over the entire range of the setup (MHz)	4 to 13.8 GHz
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Within Band 2 and Band 5
Total Bandwidth (MHz)	Full b/w for Band 2 and Band 5
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	standard
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS	
Number of subarrays	1
Number of tied array beams per subarray	As many as possible for multiple targets in the field of view (8).
Required angular resolution of a tied array beam (arcmin)	5 arcsec
Maximum baseline required (km)	8

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Required baseline sensitivity	~20 μJy/beam for 3 min integration, assuming 4km subarray, 15 GHz, 1GHz b/w and a 100m class remote telescope	
Primary beam size (FWHM, arcmin)	15 m antenna 5.3 arcmin (15 GHz, 2cm)	
Total bandwidth for each tied array beam	1 GHz (equivalent to 8 Gbps data rate for 2-bit sampling)	
Number of output channels	5 (200 MHz each centred at the centre frequency of the 256MHz standard channels for the VLBI stations)	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-MID local interferometer data using coarse VLBI visibilities) N/A		
Required angular resolution (arcmin) (single value or range)	>0.3 arcsec in Band 2 >0.06 arcsec in Band 5	
Maximum baseline required (km)	120 km	
Mapped image size (degrees)	standard FOV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	Standard	
Output bandwidth (minimum and maximum frequency - MHz)	0.81 GHz at Band 2 1 GHz at Band 5	
Required rms (Jy per beam) (if polarisation products required define for each)	6 μJy/beam for 3 min integration.	
Dynamic range within image (if polarisation products required define for each)	>10000	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. For SKA1-MID local interferometer data using normal visibilities)	
Required angular resolution (arcmin) (single value or range)	>0.23 arcsec in Band 2 >0.06 arcsec in Band 5
Maximum baseline required (km)	Full array

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Mapped image size (degrees)	standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	Full b/w 810 MHz Band 2 Full b/w 5 GHz Band 5	
Required rms (Jy per beam) (if polarisation products required define for each)	~ 6 μJy/beam	
Dynamic range within image (if polarisation products required define for each)	10000 –I, 100 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)	>0.1 arcsec in Band 5	
Maximum baseline required (km)	4 km	
Mapped image size (degrees)	5 arcsec	
Required pixel resolution (arcseconds)	standard	
Number of image channels	standard	
Channel width (kHz)	20 km/s	
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	~mas (8000 km VLBI baselines)	
Mapped image size (degrees)	Up to 5x5 arcsec per beam	
Required rms (Jy per beam) (if polarisation products required define for each)	~20 μJy/beam for 3 min integration, assuming 4 km subarray, 15 GHz, 1GHz b/w and a 100m class remote telescope	
Dynamic range within image per channel (if polarisation products required define for each)	Up to 10000 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
	X	5%

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		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be SKA1-MID interferometer images from the full array, raw visibilities and beam-formed voltage data for SKA-VLBI. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to mas level (depending on observing frequency).
Description of pipeline	Standard imaging pipeline for SKA. Standard VLBI imaging pipelines. Pipelines at SRC to beamform raw visibilities for later correlation with VLBI network
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	No time critical, similar cadence as for the external VLBI correlator (e.g. 1-2 months).

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
For Band 5 continuum imaging observations with full bandwidth (5 GHz) there are no correlator resources left for beamforming. A compromise will have to be made for continuum observations bandwidth to allow resources for beamforming (e.g. 4 GHz continuum bandwidth and 2 VLBI beams with 1 GHz b/w each). For Band 2 wide-field VLBI on targeted lensed objects, beamforming will be performed post-observing from raw SKA1-MID visibilities at e.g. the SKA science regional centres, TBD.

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

REFERENCES
[1] J. P. McKean et al, Proceedings of Advancing Astrophysics with the Square Kilometre Array (AASKA14) [2] C. Spingola et al., 2018, MNRAS, 478, 4816 [3] J. N. Winn et al., 2004, Nature, 427, 613 [4] S. A. Mao et al., 2017, Nature Astronomy, 1, 621 [5] C. Spingola et al., 2019, MNRAS, submitted (arXiv:1905.06363) [6] C. Spingola et al., 2019, A&A, submitted [7] C. M. V. Impellizzeri, 2008, Nature, 456, 927

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

1.23 IMBH: Intermediate-mass black holes

PROJECT DETAILS	
Title	**Intermediate-mass black holes**
Principal Investigator	**Mar Mezcua**
Co-Authors	**Megan Argo**
Time Request	6000 h

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
X	SKA1-MID Band 2	1500 x 3 epochs
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	1500

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	6 months monitoring for follow-up variable events (e.g. ejections in the jets), in Band 2 with 2 months cadence
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY
This project will to follow-up dwarf galaxies identified in SKA continuum survey fields with additional information from multiwavelength surveys, using the SKA-VLBI capability in Band 2 and Band 5. This project will use both beamformed data for SKA-VLBI, and simultaneous SKA1-MID interferometer images form same subarray, for complementary studies of the targets -total flux density monitoring-. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V

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

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Intermediate-mass black holes (IMBHs) with 100 < M_{BH} < 1e6 Msun are the leftover of the seed black holes that did not become supermassive. They should be found in dwarf galaxies, which are thought not to have grown significantly via accretion and mergers and thus resemble the first galaxies. The goal of this project is to probe the presence of IMBHs in dwarf galaxies and their evolution as function of cosmic time through a multifrequency survey. This will be possible thanks to the superb SKA-VLBI sensitivity (below the μJy level) at a high resolution (milliarcsec level), which will allow us to disentangle AGN activity from star formation and probe jet ejection events from IMBHs. Because radio wavelengths are less affected by gas or dust obscuration than e.g. optical or X-ray studies, such deep radio survey will allow us to trace IMBHs out to a deepness never explored before.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
		Individual fields-of-view with multiple objects
	X	Maps through multiple fields of view
	X	Non-imaging pointings (for VLBI)
Number of targets	1 large multiwavelength field, thousands of dwarf galaxies expected	
Positions of targets	Target field will be selected in coordination with another deep multi-wavelength survey.	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	1500 hours (band 2) x 3 epochs 1500 hours (band 5)	
Average peak flux density (Jy or Jy per beam)	1 μJy/beam	
Range of peak flux densities (Jy or Jy per beam)		
Expected polarised flux density (expressed as % of total)	A few %	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Within Band 2 and 5, to be determined depending on the VLBI network capability
Total Bandwidth (MHz)	1 GHz for VLBI beams
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	N/A
Temporal resolution (in seconds)	Standard Nyquist sampling

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OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Within Band 2 and 5, to determined depending on the VLBI network capability
Total Bandwidth (MHz)	1 GHz
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	200 (using coarse VLBI visibilities)
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	In principle just 1, or 2 for dual band simultaneous observations (if required)	
Number of tied array beams per subarray	As many as possible VLBI beams for targets, 1-2 beams for calibrators (10 beams maximum allowed).	
Required angular resolution of a tied array beam (arcmin)	1.5 arcsec (6 GHz, 5 cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~36.5 μJy in 1 min, 1 GHz b/w	
Primary beam size (FWHM, arcmin)	15m antenna 13 arcmin (6 GHz, 5cm)	
Total bandwidth for each tied array beam	1 GHz (equivalent to 8 Gbps data rate for 2-bit sampling)	
Number of output channels	5	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	0.2 μJy/beam	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-mid local interferometer data using coarse VLBI visibilities)	
Required angular resolution (arcmin) (single value or range)	standard for subarray
Maximum baseline required (km)	same subarray as for VLBI beams
Mapped image size (degrees)	standard FoV
Required pixel resolution (arcseconds)	standard
Number of output channels	standard
Output bandwidth (minimum and maximum frequency - MHz)	1 GHz

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Required rms (Jy per beam) (if polarisation products required define for each)	~ µJy/beam	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)		
Required angular resolution (arcmin) (single value or range)	1.5 milliarcseconds (8000 km VLBI baselines at 6 GHz)	
Mapped image size (degrees)	1.5 arcsecond for each phased-array beam	
Number of image channels	1024	
Channel width (kHz)	500 kHz	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	0.2 µJy/beam	
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-MID interferometer images from the full array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec or mas level (depending on observing frequency).
Description of pipeline	Standard imaging pipeline for SKA. Standard imaging pipeline for SKA-VLBI.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	No time critical for SDP products, coincident with external correlator results, before following observing epoch.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)

REFERENCES

Volonteri 2010, A&ARv, 18, 279
Mezcua 2017, IJMPD, 26, 1730021
Mezcua et al. 2018a, MNRAS, 478, 2576
Mezcua et al. 2018b, MNRAS Letters, 480, L74

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

1.24 ULX: Studies of Ultraluminous X-ray sources -ULXs- in the local Universe

PROJECT DETAILS	
Title	**Studies of Ultraluminous X-ray sources -ULXs- in the local Universe**
Principal Investigator	**Matt Middleton**
Co-Authors	**James Miller-Jones** **David Williams** **Rob Fender** **Stéphane Corbel** **Mickael Coriat**
Time Request	150 Hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	150 Hours

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
X	Normal	
X	Fixed schedule (give cadence)	One observation per source per week
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY

This project will monitor the following bright ultraluminous X-ray sources (ULXs) accessible to SKA1-MID using VLBI:

1. NGC 5408 X-1
2. NGC 1313 X-1
3. NGC 1313 X-2
4. NGC 55 ULX
5. NGC 7793 P13

For the monitoring it is required to perform one observation per source per week, for a total of 30 epochs per source.
Using both beamformed data for SKA-VLBI, and simultaneous SKA1-MID subarray

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interferometer images, we will obtain complementary studies of the targets at different angular scales and obtain total flux density and polarization monitoring. Interferometer images will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ()*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER () or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q
X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
We propose to monitor the brightest ULXs in the local Universe (< 5 Mpc) accessible to SKA1-VLBI. These are black holes/neutron star systems accreting at super-Eddington rates (e.g. Bachetti et al. 2014), analogues of TDEs and high redshift quasars. Jet launching has recently been shown to occur quasi-persistently (Cseh et al. 2014; 2015) but little to nothing is known about their properties. Radio-bright ejecta seen thus-far from ULXs indicate that they can be extremely bright (up to >400 µJy) although detecting them across the population has proven extremely difficult due to low observing cadence and highly variable flux densities. Their distance demands both a high sensitivity and high angular resolution if we wish to study the ejecta in detail; SKA1-VLBI is perfectly suited to this objective. Our goal is to monitor a sample of the brightest ULXs accessible to SKA1 with VLBI which will establish the first high SNR baseline for the duty-cycle of ejections in ULXs and resolve the ejecta (moving by ~1mas/month at a distance of a few Mpc). The later will constrain the dynamics and energy budget of the ejections, vital for understanding the nature of super-critical accretion flows (and also the influence on the surrounding environment).

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (VLBI beams)
Number of targets	5	
Positions of targets	ULXs accessible to SKA1-MID	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………….]
	X	NO
Time Critical?	X	YES – regular weekly monitoring is critical to sample the duty cycle of ejections
		NO
Integration time per target (hrs)	1hr/observation	
Average peak flux density (Jy or Jy per beam)	400µJy/beam	
Range of peak flux densities	10-500 µJy/beam	

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(Jy or Jy per beam)	
Expected polarised flux density (expressed as % of total)	1%

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	5000 or 8400
Total Bandwidth (MHz)	1000
Minimum and maximum frequency over the entire range of the setup (MHz)	
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Same as above
Total Bandwidth (MHz)	"
Minimum and maximum frequency over the entire range of the setup (MHz)	"
Spectral resolution (kHz)	standard
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	1 VLBI beam for target, 3 beams for calibrators.	
Required angular resolution of a tied array beam (arcmin)	1.8/1.1 arcsec (5/8.4 GHz, 6/2.3 cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~32-35 μJy in 1 min	
Primary beam size (FWHM, arcmin)	15m antenna 15.8/9.5 arcmin (5/8.4 GHz)	
Total bandwidth for each tied array beam	1 GHz (equivalent to 8 Gbps data rate for 2-bit sampling)	
Number of output channels	5 (200 MHz each centred at the centre frequency of the 256MHz standard channels for the VLBI stations)	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	1 μJy (to provide a SNR of 10 at the lowest expected fluxes)	
Dynamic range (if polarisation products required define for each)	10:1	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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

IMAGING CONSIDERATIONS (CONTINUUM. For SKA1-mid local interferometer data using normal visibilities)		
Required angular resolution (arcmin) (single value or range)	standard	
Maximum baseline required (km)	Whole array	
Mapped image size (degrees)	Standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	1 GHz	
Required rms (Jy per beam) (if polarisation products required define for each)	From 1 μJy/beam, depending on observed frequency, for 1h integration	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	
Required angular resolution (arcmin) (single value or range)	~1 mas (for 8000 km baselines)
Mapped image size (degrees)	~1-2 arcsecond for each phased-array beam

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Required rms (Jy per beam) (if polarisation products required define for each)	between SKA1 VLBI beam and a 100m-class dish is ~32-35 μJy in 1 min	
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in trigger VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be SKA1-MID interferometer images from the full array and beam-formed voltage data for SKA-VLBI, whenever triggered. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to mas level.
Description of pipeline	Standard imaging pipeline for SKA.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	Based on our example source, we require weekly observations to detect ejections with a longer baseline to constrain proper motions. SDP products should be provided before following observing epoch, preferably no later than one day after completion of the observation. VLBI beams voltage data needs to be transferred to the external correlator in a timely manner, preferably using e-VLBI mode (real-time transfer and correlation) for fast turnaround of results before next epoch.

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Selection of observing band (C or X) depending on targets characteristics.

REFERENCES
Bachetti et al. 2014, Nature, 514, 202 Cseh et al. 2014, MNRAS, 439, L1 Cseh et al. 2015, MNRAS, 452, 24

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

1.25 HI-ABS-MID: Characterising feeding and feedback in high-z radio AGN using HI absorption with SKA1-MID

PROJECT DETAILS	
Title	Characterising feeding and feedback in high-z radio AGN using HI absorption with SKA1-MID
Principal Investigator	Raffaella Morganti
Co-Authors	Robert Schulz, Tom Oosterloo, Elaine Sadler, James Allison et al.
Time Request	200 hrs

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
X	SKA1-MID Band 1	100 hrs (continuum and spectral line)
X	SKA1-MID Band 2	100 hrs (continuum and spectral line)
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-LOW array interferometer continuum and spectral line images, for complementary studies of the target -total flux density integration and polarisation studies at jet-ISM interaction sites-. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities and polarisation of the calibrators in the field, usually resolved at VLBI scales. Objects will be observed either in Band 1 or Band 2 depending on their redshift.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V

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

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q
X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
HI 21cm absorption has the main advantage that can be detected and studied at very high spatial resolution - including at milli-arcsecond scales with VLBI as long as the background source is bright enough - which is not possible for HI emission studies. Thus, associated HI absorption is used to probe the circumnuclear regions of radio-loud AGN. We know that this gas can trace very different phenomena (Morganti & Oosterloo 2018 for a review): circumnuclear disc, infalling gas connected with the triggering of the AGN, outflowing gas (Morganti et al. 2013). All have a key role for the properties of the nuclear activity and the evolution of the host galaxy. However, the full understanding and study of these phenomena requires to locate the HI and resolve the kinematics, and this is needed for objects covering a large range of redshifts. At the moment, this view of the HI on pc scale can only be done for very nearby radio AGN (z<0.1, see Schultz et al. 2018 and ref. therein). The frequency coverage and the radio-quiet location will ensure that the SKA1-MID HI surveys will trace HI absorption in high-z radio AGN providing an unprecedented view of the gas content of these objects (Morganti, Sadler & Curran 2015). The SKA1-VLBI follow up will be needed to provide for the first time a detailed view of the HI on pc scales and how it evolves from low to high-z, i.e. tracing the building up of the SMBH, the feeding of the radio and the properties of feedback. Although not a primary objective, we request full polarisation because can provide a complementary diagnostic to identify sites of strong shocks in the case of outflows originated by jet-ISM interaction (see case of 4C12.50, Morganti et al. 2013).

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (VLBI beams)
Number of targets	Minimum number of targets: 10 @ z<1 and 10 @ z>1 (1<z<3)	
Positions of targets	Individual targets within a single FoV of individual SKA1-MID station	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	10 hrs per target (on source)	
Average peak flux density (Jy or Jy per beam)	100 mJy	
Range of peak flux densities (Jy or Jy per beam)	50-500 mJy (likely higher, depends on interesting targets)	
Expected polarised flux density (expressed as % of total)	Few %	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID bands 1,2 (depending on target's redshift)

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Total Bandwidth (MHz)	500 MHz each band (4 Gbps for 2-bit sampling, per VLBI beam per band)
Minimum and maximum frequency over the entire range of the setup (MHz)	Depends on target's redshift and characteristics of HI profile
Spectral resolution (kHz)	external correlator concern
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID bands 1,2 (depending on target's redshift)
Total Bandwidth (MHz)	3.125 MHz for spectral line, 500 MHz for continuum each band
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	Standard for Mid correlator (13.44 kHz for all bands), finest resolution for zoom mode 190 Hz
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-MID dish, up to 4 VLBI beams per subarray (1 target, 3 calibrators)	
Required angular resolution of a tied array beam (arcmin)	5.4 arcsec (21 cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~38 μJy in 1 min, at L-band with 500 MHz b/w	
Primary beam size (FWHM, arcmin)	15m antenna 0.9deg (21cm)	
Total bandwidth for each tied array beam	500 MHz (equivalent to 4 Gbps data rate for 2-bit sampling, per band)	
Number of output channels	2 or 3	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel (centred at the centre frequency of the 256 MHz standard channels for the VLBI stations)	
Required rms (Jy) (if polarisation products required define for each)	1.6 μJy/beam (for 10h integration)	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-MID local interferometer data)		
Required angular resolution (arcmin) (single value or range)	0.4" (in any case, sub-arcsecond is preferred if possible)	
Maximum baseline required (km)	whole array	
Mapped image size (degrees)	standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	500 MHz bandwidth	
Required rms (Jy per beam) (if polarisation products required define for each)	2 μJy/beam (1h integration)	
Dynamic range within image (if polarisation products required define for each)	1000 –I	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth)		
Required angular resolution (arcmin) (single value or range)	0.4" (in any case, sub-arcsecond is preferred if possible)	
Maximum baseline required (km)	whole array	
Mapped image size (degrees)	standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of image channels	16384	
Channel width (kHz)	Finest resolution 190Hz	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	10^{-4} Jy/beam/ch	
Dynamic range within image per channel (if polarisation products required define for each)	100 - I	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	
Required angular resolution (arcmin) (single value or range)	~mas (8000 km VLBI baselines)
Mapped image size (degrees)	Up to 5x5 arcsec per beam
Required rms (Jy per beam) (if polarisation products required define for each)	Between SKA1 VLBI beam and a 100m-class dish is ~40-80 μJy/beam mean level for band 1 and 2, for 60sec integration, 1-sigma.

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Dynamic range within image (if polarisation products required define for each)	>50 for primary target ~1000 for calibrators	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data produced from the core (one subarray) for SKA-VLBI to obtain high frequency resolution VLBI visibilities, and simultaneous SKA1-MID interferometer images from the whole array.
Description of pipeline	Standard imaging pipeline for SKA1-MID Standard imaging pipeline for SKA-VLBI data, spectral line pipelines.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.)	For SDP products no time critical, similar cadence as for the external VLBI correlator (e.g. 1-2 months). VLBI voltage beams data need to be sent to the external correlator in a couple of weeks after the observation was performed.

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
RFI can be an issue at these frequencies. The availability of a number of candidates from the SKA-MID survey will allow us to choose the best for the follow up with the VLBI network. Arranging for arrays co-observing at these frequencies (redshifted HI) together with SKA.

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

1.26 FRB: Fast Radio Bursts and their hosts with SKA-VLBI

PROJECT DETAILS	
Title	**Fast Radio Bursts and their hosts with SKA-VLBI**
Principal Investigator	**Zsolt Paragi**
Co-Authors	**Jason Hessels, Benito Marcote, Aard keimpema, Alexander Plavin**
Time Request	750 h

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Forming multiple tied-array beams for VLBI as well as pulsar timing simultaneously (SKA core), plus providing SKA interferometer products preferably for the whole array is a precondition to this project.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
X	SKA1-MID Band 2	750 h
	SKA1-MID Band 3	
	SKA1-MID Band 4	
	SKA1-MID Band 5	

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
X	Normal	Some of the runs will be regular SKA-VLBI observations that target FRB hosts / persistent radio counterparts
	Fixed schedule (give cadence)	
X	Time-critical override	Some of the SKA-VLBI observations will be triggered by either SKA1-MID (and/or LOW) transient KSP observations, or by an external "FRB finding machine". The goal is to target repeating FRBs when they are in their active phase.
	Custom Experiment	
X	Commensal	Possibly, with SKA1-MID transient follow-ups and Pulsar Search, simultaneously Pulsar Timing
X	Collaborative & Coordinated	Will have to coordinate the SKA-VLBI observations with radio observatories.
X	Sub-arrays required	beamforming for up 8 km baselines

COMMENTS ON OBSERVING STRATEGY
This project will include part time regular, part time time-critical observations. The regular observations will target either known FRB hosts, or galaxies that potentially host FRBs. In both cases we will use VLBI and pulsar search beams as well. In the latter case a

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broad range of dispersion measures (DM) will be searched for. The time-critical SKA-VLBI observations will be triggered by either a SKA1-MID/LOW itself (following e.g. transient KSP detections), or by external telescopes (e.g. ASKAP). Pulsar beams will be needed to search for FRBs during the run. We will only trigger on already known repeaters, so the approximate position (~arcsec level) and the DM of those FRBs will be known prior to the observations. Besides the VLBI and pulsar search beams, SKA interferometer images will be required for better calibration of the VLBI data products.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or CORRELATOR (_)*			
X	X (or RCP)		Stokes **I**
X	Y (or LCP)		Stokes Q
	XY		Stokes U
	YX		Stokes V

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (__) or CORRELATOR (X)*			
X	XX (linear products may be used by SDP for phasing-up the array / calibrating the beam-formed data)	**X**	Stokes **I** (total intensity and polarization maps from the simultaneous SKA1-MID array data have immediate scientific value)
X	YY	**X**	Stokes Q
X	XY	**X**	Stokes U
X	YX	**X**	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Fast Radio Bursts (FRB) are highly dispersed millisecond-duration pulses of extragalactic origin (Lorimer et al. 2007). Localization of the hosts of these bursts, to prove their extragalactic origin was extremely difficult, because most of these are one-time events. The first source that was seen multiple times, the repeater FRB121102 was successfully localized to a dwarf galaxy by the VLA (Chatterjee et al. 2017) and the EVN (Marcote et al. 2017). Dedicated FRB search machines (e.g. ASKAP and CHIME) have discovered a great number of FRB sources recently, including several new repeaters as well (Shannon et al. 2018; CHIME/FRB Collaboration 2019). By the time the phase-I SKA telescopes are built, there will likely be 1000s of sources, which will make cosmological studies possible. Sub-arcsecond localization with VLBI will likely still be unique, however. There are various ways VLBI can play an important role in FRB research. It will be possible to study faint, persistent counterparts at milliarcsecond resolution to understand their origin. One may also target faint radio sources that show the properties of the FRB 121102 counterpart, and lie in similar environments, while simultaneously looking for dispersed, millisecond-duration pulses (Marcote et al. 2019). As for the known repeaters, we can target them to achieve milliarcsecond precision localization. This may be on the one hand important for relatively nearby events, to establish accurate positions within their hosts (e.g. to find out whether they are related to star forming regions or not). On the other hand for those FRBs at higher redshifts and especially for those residing in dwarf galaxies, identification of the hosts may require a precision well below sub-arcsecond (cf. Eftekhari et al. 2017). We propose a SKA-VLBI follow-up program of a population of repeaters and (candidate or known) FRB hosts in order to probe them on milliarcsecond scales. Polarization information will be critical because some of the FRBs lie in extreme magnetoionic environments (Michilli

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et al. 2018). FRB scintillometry with SKA-VLBI, while it will not resolve the emitting regions in hese extragalactic sources, it will provide valuable information on the nature of the scattering screen local to the source (cf. Pulsar Scintillometry Use Case by Kirsten et al.).

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	4 – primary target (**note 2 beams: 1 VLBI and 1 pulsar timing**) plus minimum 1, ideally at least 3 ~>1 mJy calibrators	
Positions of targets	All within a single FoV of individual SKA1-MID dishes	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………………..]
	X	NO
Time Critical?	X	YES [details: details: Target of Opportunity requiring rapid response within a few days]
		NO
Integration time per target (hrs)	Ranges from few hours to ~12 hours - depending on target. For FR host characterization we would prefer a longer integration to build up *uv*-coverage. For FRB pulse detection we simply need long integrations to detect a burst. Note there is additional overhead time required if correlation is done real time (e-VLBI).	
Average peak flux density (Jy or Jy per beam)	~10^{-3} Jy/beam peak brightness for persistent sources, ~1 Jy ms fluence for FRB bursts	
Range of peak flux densities (Jy or Jy per beam)	~10^{-4} -- 10^{-2} Jy/beam peak brightness ~0.1 -- 30 Jy ms fluence range for bursts	
Expected polarised flux density (expressed as % of total)	1% for persistent counterparts; up to 100% in FRB bursts, but the rotation measure may be extremely high (RM > 10^5 rad m^{-2})	

OBSERVATIONAL SETUP : *BEAMFORMER (**X**) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID Band 2 centre
Total Bandwidth (MHz)	512 MHz / polarization for MID (equivalent of 4 Gbit/s/beam for 2-bit sampling)
Minimum and maximum frequency over the entire range of the setup (MHz)	Central frequency ±256 MHz
Spectral resolution (kHz)	Minimum 500 kHz (external correlator concern)
Temporal resolution (in seconds)	Standard Nyquist sampling (VLBI data integration time will be 1-2s at the VLBI correlator; these spectral and time resolutions will allow several arcsec FoV for each target)

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (**X**)*	
Central Frequencies (MHz) (including redshift, observatory correction)	See above

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Total Bandwidth (MHz)	See above
Minimum and maximum frequency over the entire range of the setup (MHz)	See above
Spectral resolution (kHz)	500 kHz (standard)
Temporal resolution (in seconds)	1s standard

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	5 (1 VLBI and 1 pulsar timing beam for the target, 3 beams for calibrators)	
Required angular resolution of a tied array beam (arcmin)	The 'angular resolution' of the tied array beam is the 'FoV' for a single pointing in our SKA-VLBI observation. Depending on the a-priori localization of our FRB targets, we may decide to phase-up a more compact core array to increase our FoV to >>arcsec.	
Total bandwidth for each tied array beam	512 MHz / polarization (equivalent of 4 Gbit/s/beam for 2-bit sampling)	
Maximum baseline required (km)	4 km core (8 km baselines)	
Primary beam size (sq degrees)	>0.01	
Number of output channels	3 (200 MHz each centred at the centre frequency of the 256MHz standard channels for the VLBI stations)	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel per polarization	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations)		
Required angular resolution (arcmin) (single value or range)	0.03 (200 mas)	
Maximum baseline required (km)	150 km	
Mapped image size (degrees)	0.05 (20 arcsec)	
Required pixel resolution (arcseconds)	0.05 arcsec	
Number of output channels	4760	
Output bandwidth (minimum and maximum frequency - MHz)	2380 MHz	
Required rms (Jy per beam) (if polarisation products required define for each)	$3\mathrm{x}10^{-7}$ Jy/beam; assuming all telescopes	
Dynamic range within image (if polarisation products required define for each)	300 -- I, 30 -- Q/U/V (for primary target)	
Absolute flux scale calibration	X	1-3%

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		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (VLBI)		
Required angular resolution (arcmin) (single value or range)	$5x10^{-3}$ arcsec (this will depend on the SKA-VLBI array configuration, and data weighting)	
Mapped image size (degrees)	Up to 5x5 arcsec per beam (typically 1x1 arcsec is sufficient when the source position is known at the sub- arcsecond level)	
Required rms (Jy per beam) (if polarisation products required define for each)	$1.5x10^{-6}$ Jy/beam for persistent counteparts. Note this sensitivity is achievable with SKA1-MID plus the EVN for example. We assumed 81% of SKA1-MID core (inner 4 km) is phased-up, providing a rebaselined SEFD of 5 Jy. ~100 mJy ms for single pulse detection.	
Dynamic range within image (if polarisation products required define for each)	>50 for primary target ~1000 for calibrators	
Absolute flux scale calibration	**X**	1-3%
		5%
		10%
		20-50%
		n/a

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DATA ANALYSIS	
Procedures required	We require well established policies on how SKA1-MID will respond to external and internal triggers. In addition, well established policies are needed for arranging ToO/trigger style of observations together with a global SKA-VLBI network.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	Beam-formed data degradation due to shadowing and/or cross-talk should not be underestimated. Will likely need a real-time monitoring system of what telescopes contribute to the beam-formed data. SEFD estimates should accurately reflect the situation when part of the array does not contribute to beam-formed data.
Data products	We indicated above that we need both beam-forming for SKA-VLBI and for pulsar searching simultaneously from the core; whole array SKA1-MID interferometer data/products will be necessary as well (coarse channelization is fine). The latter will be extremely valuable for total flux density and polarization monitoring of the target, and at the same time for the accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field. (Note for VLBI we do not have primary flux density calibrators, therefore the calibration of the individual telescopes is usually based on measured Tsys, and a-priori assumed telescope gain; having VLBI targets with accurately known flux densities at the epoch of observation will help VLBI calibration.)
Description of pipeline	**(Near-) real-time pulsar pipeline results will be important for the FRB burst detection runs.** Imaging pipeline results are not time critical in any of the cases (neither for host characterization nor for FRB searches).
Quality assessment plan & cadence	The 4 VLBI beams will be streamed (either real-time, or after buffering) to a VLBI correlator centre, that will give feedback on the VLBI data products in either real-time, or ideally within 1-2 days.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.	For the pulsar pipeline, preferably real-time or at least within a few days, if possible.

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
The same SKA-VLBI issues apply as in the SKA1-MID synchrotron transient follow-up use case. The additional requirement here is the introduction of simultaneous pulsar timing beam. **Care must be taken that the pulsar beam data and the VLBI data products are perfectly aligned in time, because VLBI detection of an FRB pulse requires correlation of just one integration of ~1 millisecond. This is not just a question of time stamps, it also implies that the pulsar beam and the VLBI data are de-dispersed exactly the same way. This requires coordination between CSP and the external VLBI correlator.**

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

1.27 HIGHz-AGN: Extremely high-redshift AGN with SKA-VLBI

PROJECT DETAILS	
Title	**Extremely high-redshift AGN with SKA-VLBI**
Principal Investigator	**Krisztina Perger (ELTE)**
Co-Authors	**Sándor Frey (Konkoly Obs.), Krisztina Gabányi (ELTE), Leonid Gurvits (JIVE), Zsolt Paragi (JIVE)**
Time Request	2000

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
X	SKA1-MID Band 2	4 hrs per field
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	4 hrs per field

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	While not strictly time critical, ideally the two frequency band observations should be close in time, within a few weeks preferably for more reliable spectral index measurement (in case the target is variable).
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 km inner core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-MID array interferometer images at two frequencies, for complementary studies of the target at different angular scales and total flux density and polarization imaging. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales.

POLARISATION PRODUCTS REQUIRED: *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED: *BEAMFORMER ( ) or SKA CORRELATOR (X)*			

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X	XX	**X**	Stokes I
X	YY	**X**	Stokes Q
X	XY	**X**	Stokes U
X	YX	**X**	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
Active galactic nuclei (AGN) at very high redshifts (*z*>4) can be mapped up to mas scales using coordinated SKA1-MID and global VLBI observations, at a high resolution and sensitivity. SKA-VLBI provides a way to distinguish between radio emission originating either from AGN activity or star formation, and it provides information on the feedback processes between the AGN and the host galaxy (Thomson et al. 2019). Dual-frequency observations would facilitate the distinction between flat-spectrum cores and steeper-spectrum jet features, thus enabling identification of blazars and misaligned radio-loud AGN. Phasing up the core of SKA1-MID will allow to form several beams to target and nearby calibrator sources to obtain deep, thermal noise-limited images (Paragi et al., 2014). The fraction of radio-detected high-redshift AGN is <7% (Perger et al., 2017), and there could be an underlying population of optically identified radio sources below the radio detection threshold. We estimated an average flux density of ~50 µJy for these hidden sources (Perger et al., in prep.). Detection of the higher end of the radio quiet high redshift AGN population would be possible with SKA-VLBI arrays in ultra-deep surveys with 1 µJy thermal sensitivity for multiple sources, by taking advantage of the SKA1-MID multi-beam capability.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (for VLBI)
Number of targets	Up to 10 targets per field (limited by Band 5 simultaneous VLBI and imaging requirements).	
Positions of targets	Individual targets within a single FoV of individual SKA1-MID dishes	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………….]
	X	NO
Time Critical?		YES [details: ……………………………………….]
	X	NO
Integration time per target (hrs)	4 hrs per frequency band	
Average flux density or peak brightness (Jy or Jy per beam)	~50 µJy	
Range of flux density or peak brightness (Jy or Jy per beam)	~1 - 100 µJy	
Expected polarised flux density (expressed as % of total)	A few %	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	1.4 GHz (SKA1-MID Band 2 centre) 5.4 GHz (SKA1-MID Band 5 low-end)
Total Bandwidth (MHz)	810 MHz for Band 2 (whole band) 1 GHz for Band 5
Minimum and maximum frequency over the	0.95 -1.76 GHz

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entire range of the setup (MHz)	4.9 - 5.9 GHz
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	1.4 GHz (SKA1-MID Band 2 centre) 5.4 GHz (SKA1-MID Band 5 low-end)
Total Bandwidth (MHz)	810 MHz for Band 2 (whole band) 1 GHz for Band 5
Minimum and maximum frequency over the entire range of the setup (MHz)	0.95 -1.76 GHz 4.9 - 5.9 GHz
Spectral resolution (kHz)	Standard for Mid correlator
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1 (2 for dual frequency)	
Number of tied array beams per subarray	Depends on number of high redshift targets in a particular field, within the FoV of a matching 25m/100m telescope in the VLBI array. With 3+ calibrators and 5+ targets the expected number of beams is order of 10, only 8 provided.	
Required angular resolution of a tied array beam (arcmin)	N/A (the beam resolution is the field of view of our individual pointing; if it is not smaller than about 1 arcsec, we are ok, because the targets are expected to be very compact [AGN case] or completely resolved out [SF case]).	
Maximum baseline required (km)	8	
Required baseline sensitivity	Between SKA1-MID VLBI beam and a 100m-class dish is ~30 μJy/beam in 1 min for Band 2 & 5.	
Primary beam size (FWHM, arcmin)	Matching VLBI array primary beam size will range from 10-30 arcmin and 3-10 arcmin for Band 2 and Band 5, respectively.	
Total bandwidth for each tied array beam	For MID 810/1024 MHz (equivalent to 6.25/8 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	4-5	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel for MID	
Required rms (Jy) (if polarisation products required define for each)	N/A	
Dynamic range (if polarisation products required define for each)	N/A	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-LOW/MID local interferometer data)		
Required angular resolution (arcmin) (single value or range)	For MID 0.1-0.3 arcsec depending on frequencies	
Maximum baseline required (km)	Whole MID array	
Mapped image size (degrees)	Standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	Standard (normal visibilities)	
Output bandwidth (minimum and maximum frequency - MHz)	800 MHz bandwidth for Band 2 1000 MHz bandwidth for Band 5	
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-MID continuum sensitivities for Band 2/5 (at least 1×10^{-6} Jy/beam)	
Dynamic range within image (if polarisation products required define for each)	500 -I, 5-50 -Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	
Required angular resolution (arcmin) (single value or range)	A few mas for MID (depending on obs. frequency, VLBI array config., data weighting)
Mapped image size (degrees)	Up to 5x5 arcsec per beam
Required rms (Jy per beam) (if polarisation products required define for each)	1×10^{-6} Jy/beam

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

Dynamic range within image (if polarisation products required define for each)	~50 for primary target ~1000 for calibrators	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-MID interferometer images from the full arrays (with limited bandwidth in case of Band 5). The SKA-VLBI data products will be produced by an external correlator.
Description of pipeline	Standard imaging pipeline for SKA1-MID, standard VLBI pipelines for SKA-VLBI data.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.)	Upon completion of scheduling block and pipeline reduction, before next observing frequency is performed.

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

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
To get practically thermal noise limited data on the primary target, having ~>1 mJy compact calibrator(s) in the FoV is a basic requirement for this observation, ie. multiple-beam capability is a must (several targets + minimum 3 calibrators). SKA1-MID correlator processing resources are limited, for full b/w Imaging in Band 2 and 1GHz in Band 5 using standard visibilities, only 8 VLBI beams will be available with 1 GHz b/w. More VLBI beams may be needed for some fields.

REFERENCES
Thomson et al. 2019, Studying galaxy evolution through cosmic time via the µJy radio population: early results from eMERGE, arXiv:1902.02356 Paragi et al. 2014, Very Long Baseline Interferometry with the SKA, 2015aska.confE.143P Perger et al. 2017, A Catalog of Active Galactic Nuclei from the First 1.5 Gyr of the Universe, 2017FrASS...4....9P

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

1.28 MC-METH: SKA-Mid Ultra-Precise Astrometry to the LMC and SMC

PROJECT DETAILS	
Title	**SKA-Mid Ultra-Precise Astrometry to the LMC and SMC**
Principal Investigator	**Maria Rioja**
Co-Authors	**Richard Dodson, Mareki Honma, Hiroshi Imai**
Time Request	4000 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array. 100% of core SKA1-mid collecting area phased up, simultaneous availability of LBA (Long Baseline Array), AVN (African VLBI Network) and EVN (European VLBI Network) antennas.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	4000 Hrs

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	8 epochs over a 2 year period close to the date where the parallax signature is largest (March and September)
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
	Sub-arrays required	

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-MID array interferometer continuum and spectral line images, for accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. Need at least 1+7 VLBI beams for 1 target and 7 calibrators for 1 microarcsec astrometry. Refer to M-VIEW case (1.1) for Multi-view requirements.

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q

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	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR _X_)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)

PM studies of the SMC/LMC by HST [1] have suggested that the SMC is currently moving around 380 km/s, which is significantly faster than previously thought (300km/s). If correct the MCs will not be bound to the Milky Way. That in turn influences our expectations for the growth of galactic structure.

Recent studies have suggested that systematic astrometric accuracies of 1us are possible [2,3]. With these accuracies we could directly measure the parallax of methanol masers in the LMC to 10% accuracy. This would allow us to determine with high precision the internal rotation of the SMC/LMC dwarf galaxies and their motion around our Galaxy, revealing whether they are bound or unbound [4]. Currently there are ~20/4 detections of H2O masers [5/6] in the LMC/SMC respectively. We can assume that SKA will find significantly more than that, for methanol 6.7GHz masers. We scale by a factor of 2, which we believe is cautious.

If we assume astrometry to ~1000 of the beam we need to focus on the methanol 6.7GHz masers. These would to be strong enough to provide DR of 1000 for a 2kHz channel. To reduce non-atmospheric systematics to the thermal limit the number of beams would be 8 (ideally).

Simultaneous MID interferometer products are not needed per se, but will increase the science that can be extracted, such as detections and measurement of expansion of compact HII regions and their synchrotron radiation.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')		Individual pointings per object
	X	Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	50	
Positions of targets	All in LMC (05:23 -69:45)	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………..]
	X	NO
Time Critical?		YES [details: ……………………………………..]
	X	NO
Integration time per target (hrs)	10 (1000 DR 3mJy over 2kHz 5 ants = 10hr)	
Average peak flux density (Jy or Jy per beam)	1 (extrapolated from typical peak flux: 200Jy at 3kpc = 1 Jy at 50kpc)	
Range of peak flux densities (Jy or Jy per beam)	10-0.3	
Expected polarised flux density (expressed as % of total)	A few %	

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OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	6666 – 6672 MHz
Total Bandwidth (MHz)	1 GHz (dual polarization)
Minimum and maximum frequency over the entire range of the setup (MHz)	6100 - 7100
Spectral resolution (kHz)	2 kHz for 2 MHz around maser frequency, standard continuum for full 1GHz band (external correlator concern)
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Same as above
Total Bandwidth (MHz)	“
Minimum and maximum frequency over the entire range of the setup (MHz)	“
Spectral resolution (kHz)	200 (using coarse VLBI visibilities)
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	Full array	
Number of tied array beams per subarray	1 VLBI beam for target, 7 beams for calibrators.	
Required angular resolution of a tied array beam (arcmin)	0.1 arcsec or larger	
Maximum baseline required (km)	The full array, as maser sensitivity will be the limiting issue.	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~40 μJy in 1 min	
Primary beam size (sq degrees)	0.015 square deg (SKA1-mid 6.7 GHz FoV)	
Total bandwidth for each tied array beam	1GHz (equivalent to 8 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	80 (200 MHz each centred at the centre frequency of the 256MHz standard channels for the VLBI stations)	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)	1 μJy beam^{-1} continuum 1 mJy/beam line	
Dynamic range (if polarisation products required define for each)	1000:1	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-mid local interferometer data using coarse VLBI visibilities)		
Required angular resolution (arcmin) (single value or range)	0.6" (in any case, sub-arcsecond is preferred if possible)	
Maximum baseline required (km)	Whole array	
Mapped image size (degrees)	Standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	1000 MHz	
Required rms (Jy per beam) (if polarisation products required define for each)	N/A	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)	0.6" (in any case, sub-arcsecond is preferred if possible)	
Maximum baseline required (km)	Longest for highest resolution	
Mapped image size (degrees)	1	
Required pixel resolution (arcseconds)	0.2	
Number of image channels	1000	
Channel width (kHz)	2kHz	
Required rms (Jy per beam per channel) (if polarisation products required define for each)	Best possible	
Dynamic range within image per channel (if polarisation products required define for each)	Best possible	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	
Required angular resolution (arcmin) (single value or range)	1.2 milliarcseconds (8000 km VLBI baselines at 6.7 GHz)
Mapped image size (degrees)	0.1 arcsecond for each phased-array beam (one for maser), remaining on background calibrator targets within FoV
Number of image channels	1000
Channel width (kHz)	2kHz (line) 1MHz (continuum)

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Required rms (Jy per beam per channel) (if polarisation products required define for each)	1 mJy beam^{-1} (line) / 1 µJy beam^{-1} (calibrators)	
Dynamic range within image per channel (if polarisation products required define for each)	1000:1	
Absolute flux scale calibration		1-3%
		5%
	X	10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well-established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-MID interferometer images from the full array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps (mas) of the calibrators and targets, with uas relative astrometric accuracy of the targets.
Description of pipeline	Standard imaging pipeline for SKA. Beamformer: Streaming of data to appropriate VLBI correlator. Data rate for phased SKA-mid is 8 Gbps per beam, although project could utilise higher data rates, if they were available. Data from outstations (LBA, AVN etc) also to be streamed to VLBI correlator site.
Quality assessment plan & cadence	Records of delays, phases, fringe rates.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	Not time critical, Upon completion of scheduling block and pipeline reduction, before next observing epoch.

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
Whilst the MultiView ionospheric residuals have been shown to allow uas accuracy, the same has not been done for the troposphere. We have assumed the same scaling. Tests are required and the PIs will investigate this with the pathfinders.

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Calibrator stability has not been tested at the sub-uas level. The studies of [7,8] suggest this will be at least better than 10uas. We have requests more than the minimum number of calibrators to address this.

Size of the tied-array core for beamforming will be chosen depending on the uncertainty of the masers positions.

REFERENCES

1 Kallivayalil et al. 2006, *Is the SMC Bound to the LMC? The HST Proper Motion of the SMC*, **2006ApJ...652.1213K**

2 Rioja et al. 2017; *MultiView High Precision VLBI Astrometry at Low Frequencies*, **2017AJ....153..105R**

3 Dodson et al. 2018; *Investigations on MultiView VLBI for SKA*, **PoS(EVN2018)086**

4 Imai, et al., 2016, *Radio Astrometry towards the Nearby Universe with the SKA*, **2016arXiv160302042I**

5 Imai, et al., 2013, *ATCA survey of H2O masers in the Large Magellanic Cloud*, **2013MNRAS.432L..16I**

6 Breen, et al., 2013, *Discovery of four water masers in the Small Magellanic Cloud* **2013MNRAS.432.1382B**

7 Rioja et al., 2000, *A phase-reference study of the quasar pair 1038+528A/B*, **2000A&A...355..552R**

8 Fomalont, et al., 2011, *The Position/Structure Stability of Four ICRF2 Sources*, **2011AJ....141...91F**

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

1.29 FLARES: Triggered VLBI of Superflares on Low-Mass Stars

PROJECT DETAILS	
Title	**Triggered VLBI of Superflares on Low-Mass Stars**
Principal Investigator	**Jackie Villadsen**
Co-Authors	
Time Request	~100 (flexible)

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	~100

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
	Fixed schedule (give cadence)	
X	Time-critical override	Triggered by wide-FOV, high-cadence transient facilities (such as Evryscope and Swift BAT), with possible follow-up observations depending on the flare.
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 inner Km core

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data for SKA-VLBI, and simultaneous full SKA1-MID array interferometer images, for complementary studies of the target at different angular scales and total flux density and polarization monitoring. It will also allow accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. These observations are triggered by wide-FOV, high-cadence transient facilities, the faster on target the better (within minutes is ideal, within 1 day is max). Large stellar radio flares could last for hours to days, so follow-up observations are contemplated. e-VLBI mode is needed for fast turnaround of results.

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

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ( )*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER ( ) or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY	X	Stokes Q
X	XY	X	Stokes U
X	YX	X	Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)

Energetic particles from stellar flares are predicted to deplete ozone from planetary atmospheres [1], impacting habitability and biosignatures. Radio wavelengths offer the only means to detect non-thermal electrons in stellar flares and thereby observationally constrain flare particle acceleration. The electron energy distribution can be modelled from the radio luminosity of stellar gyrosynchrotron flares, but the electron properties are degenerate with source size and magnetic field strength [2]. VLBI observations of stellar flares can break this degeneracy by measuring source size and position [3], comparing position to stellar magnetic maps [4] to infer magnetic field strength, enabling measurement of the energetic electron properties. These measurements can be combined with existing solar data to predict the energetic particle flux around flaring stars.

Superflares are rare (monthly to yearly), high-energy flares, predicted to have dramatic impacts on planetary atmospheres around M dwarfs [5]. Due to the rarity of superflares, VLBI observations can be triggered from wide field of view transient monitoring facilities, including Evryscope (optical) and Swift BAT (gamma ray). Based on past radio observations [2], including one triggered by Swift [6], we expect large stellar radio flares to peak at flux densities of 10-100 mJy and last for hours to days.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings
Number of targets	30 (3 hours per target to improve uv coverage and measure flare decay timescale)	
Positions of targets	Individual targets within a single FoV of individual SKA1-MID dish	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ……………………………………….]
	X	NO
Time Critical?	X	YES [details: The faster on target the better – within minutes is ideal, within 1 day is max]
		NO
Integration time per target (hrs)	For SKA1-MID: 50 microJy/beam for band 5b, for 60sec integration, 1-sigma. The observation time is determined by need for uv coverage and astrometric accuracy; the sensitivity is enough to measure time variability of source structure.	
Average peak flux density (Jy or Jy per beam)	Typical flux density ~30 mJy at 12 GHz	
Range of peak flux densities	10-100 mJy	

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(Jy or Jy per beam)	
Expected polarised flux density (expressed as % of total)	0-40% polarization (circular expected, linear possible)

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR ( )*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID band 5b
Total Bandwidth (MHz)	1025 MHz (widest possible)
Minimum and maximum frequency over the entire range of the setup (MHz)	14.3-15.3 GHz (any RFI-free frequency in this range, higher is better)
Spectral resolution (kHz)	Minimum 500 kHz (external correlator concern)
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	SKA1-MID band 5b
Total Bandwidth (MHz)	1025 MHz (widest possible)
Minimum and maximum frequency over the entire range of the setup (MHz)	14.3-15.3 GHz (any RFI-free frequency in this range, higher is better)
Spectral resolution (kHz)	Standard for Mid correlator
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	Depends on number of targets/calibrators within a single FoV of individual SKA1-MID dish, at least 4 (1 target + 3 calibrators)	
Required angular resolution of a tied array beam (arcmin)	0.6 arcsec (15 GHz, 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	Between SKA1-MID VLBI beam and a 100m-class dish is ~ 50 microJy in 1 min for Band 5b (50% receivers).	
Primary beam size (FWHM, arcmin)	15m dishes 0.09deg (15 GHz)	
Total bandwidth for each tied array beam	For MID 1024 MHz (equivalent to 8 Gbps data rate for 2-bit sampling per VLBI beam)	
Number of output channels	5	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel for MID	
Required rms (Jy) (if polarisation products required define for each)	10 uJy RMS for studying time variability; longer integrations to improve uv coverage and astrometric accuracy	
Dynamic range (if polarisation products required define for each)	300 I, 30 Q/U/V	
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%

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		n/a

IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-LOW/MID local interferometer data)		
Required angular resolution (arcmin) (single value or range)	For MID 0.2 arcsec for highest frequencies, up to 1 arcsec for the lowest frequencies	
Maximum baseline required (km)	Full MID array	
Mapped image size (degrees)	Standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	1024 MHz bandwidth for Band 5b	
Required rms (Jy per beam) (if polarisation products required define for each)	Typical SKA1-MID continuum sensitivities for Band 5b (from $1.7\square10^{\square6}$ to $15.6\square10^{\square6}$ Jy/beam for 1h integration)	
Dynamic range within image (if polarisation products required define for each)	300 -I, 30 -Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	
Required angular resolution (arcmin) (single value or range)	~mas for MID (depending on obs. frequency, VLBI array config., data weighting) – expected source size of 1-3 mas

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<table>
<tr><td>Mapped image size (degrees)</td><td colspan="2">Up to 5x5 arcsec per beam</td></tr>
<tr><td>Required rms (Jy per beam)
(if polarisation products required define for each)</td><td colspan="2">Between SKA1-MID VLBI beam and a 100m-class dish is ~ 50 microJy in 1 min for Band 5b.</td></tr>
<tr><td>Dynamic range within image
(if polarisation products required define for each)</td><td colspan="2">>50 for primary target

~1000 for calibrators</td></tr>
<tr><td rowspan="5">Absolute flux scale calibration</td><td></td><td>1-3%</td></tr>
<tr><td>X</td><td>5%</td></tr>
<tr><td></td><td>10%</td></tr>
<tr><td></td><td>20-50%</td></tr>
<tr><td></td><td>n/a</td></tr>
</table>

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous interferometer images from the whole array. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to mas level (depending on observing frequency).
Description of pipeline	Standard imaging pipeline for SKA1-MID, standard VLBI pipelines for SKA-VLBI data.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to 'at completion of the full project'.)	Upon completion of scheduling block and pipeline reduction. VLBI data preferably correlated in real-time (e-VLBI mode).

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

ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)
To get practically thermal noise limited data on the primary target, having ~>1 mJy compact calibrator(s) in the FoV is a basic requirement for this observation, ie. multiple-beam capability is a must (1 target + 3 calibrators). Fast response from the VLBI network to triggers (within one day).

REFERENCES

[1] Tilley et al. 2019, Astrobiology, 19, 64

[2] Osten et al. 2005, ApJ, 621, 398

[3] Benz et al. 1998, A&A, 331, 596

[4] Morin et al. 2008, MNRAS, 390, 567

[5] Segura et al. 2010, Astrobiology, 10, 751

[6] Fender et al. 2015, MNRAS, 446, 66L

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

1.30 RADIOS: Radio and Gaia reference frames tie with radio stars

PROJECT DETAILS	
Title	**Radio and Gaia reference frames tie with radio stars**
Principal Investigator	**Bo Zhang**
Co-Authors	**Shuangjing Xu**
Time Request	500 hours

FACILITY		Preconditions
	SKA1-LOW	
X	SKA1-MID	Observations to be arranged jointly with a VLBI array.

RECEIVER(S) REQUIRED		Time (hrs)
	SKA1-LOW	
	SKA1-MID Band 1	
	SKA1-MID Band 2	
	SKA1-MID Band 3	
	SKA1-MID Band 4	
X	SKA1-MID Band 5	500h at 15 GHz

OPERATIONAL MODE (as defined in Concept-of-Operations)		Details
	Normal	
X	Fixed schedule (give cadence)	6 epochs over a 1-2 year period close to the date where the parallax signature is largest (about every 2-4 months)
	Time-critical override	
	Custom Experiment	
	Commensal	
X	Collaborative & Coordinated	VLBI
X	Sub-arrays required	4 km inner core subarray

COMMENTS ON OBSERVING STRATEGY
This project will use both beamformed data from a subarray for SKA-VLBI, and simultaneous full SKA1-MID same subarray interferometer images, for accurate calibration of the VLBI data products, by measuring total flux densities of the calibrators in the field, usually resolved at VLBI scales. Sources need to be observed at 6 epochs spread over 18-24 months at times when the parallax signature is greatest, and approximately every 2-4 months to properly sample proper motions and accelerations.

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

POLARISATION PRODUCTS REQUIRED : *BEAMFORMER (X) or SKA CORRELATOR ()*			
X	X		Stokes I
X	Y		Stokes Q
	XY		Stokes U
	YX		Stokes V
POLARISATION PRODUCTS REQUIRED : *BEAMFORMER () or SKA CORRELATOR (X)*			
X	XX	X	Stokes I
X	YY		Stokes Q
X	XY		Stokes U
X	YX		Stokes V

SCIENTIFIC DESCRIPTION (max 200 words)
How to align the radio and optical celestial reference frames (CRFs) is a key question of fundamental astrometry. The frame link is supposed to be achieved using common extragalactic objects, i.e., quasars, observed at both radio and optical wavelengths. However, the accuracy of the frame link based on quasars is limited by several factors: the different locations of radio and optical brightness centroids and the core-shift effect; radio source structure, which is generally variable; asymmetry of galaxy optical brightness with respect to core (Zacharias & Zacharias 2014, Malkin 2016). Radio star is another common celestial object which can be used for the alignment of CRFs. Compare to quasars, the proper motions of radio stars offer crucial information for estimating the rotation rates between the two CRFs (Froeschle & Kovalevsky 1982), while parallaxes can add one more dimensional coordinate component to estimate the scale of the frames; Gaia position accuracy of radio stars are much better than quasars, since most of quasars are very weak at optical wavelengths. We propose to measure parallax (and proper motion) of ~500 radio stars with accuracy at the level of 10 µas, this will help us to estimate the Gaia parallax zero point with an uncertainty of 0.6 µas, and align the frames with a precision of < 5 µas in orientation and < 0.5 µas/yr in rate.

'TARGETS' OF OBSERVATIONS		
Type of observation (what defines a 'target')	X	Individual pointings per object
		Individual fields-of-view with multiple objects
		Maps through multiple fields of view
	X	Non-imaging pointings (VLBI beams)
Number of targets	500, stronger targets	
Positions of targets	Retrieved from the Gaia celestial reference frame	
Rapidly changing sky position? (e.g. comet, planet)		YES [details: ………………………………………..]
		NO
Time Critical?	X	YES [details: …parallax observations with certain cadence…………………………………..]
		NO
Integration time per target (hrs)	1/6 Hrs per target at 15 GHz	
Average peak flux density (Jy or Jy per beam)	0.001	
Range of peak flux densities (Jy or Jy per beam)	0.0005-0.100	
Expected polarised flux density (expressed as % of total)	A few %	

OBSERVATIONAL SETUP : *BEAMFORMER (X) or CORRELATOR (_)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Band 5b at 15 GHz

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Total Bandwidth (MHz)	1 GHz
Minimum and maximum frequency over the entire range of the setup (MHz)	
Spectral resolution (kHz)	external correlator concern
Temporal resolution (in seconds)	Standard Nyquist sampling

OBSERVATIONAL SETUP : *BEAMFORMER (_) or CORRELATOR (X)*	
Central Frequencies (MHz) (including redshift, observatory correction)	Same as above
Total Bandwidth (MHz)	“
Minimum and maximum frequency over the entire range of the setup (MHz)	“
Spectral resolution (kHz)	200 (using coarse VLBI visibilities), 13.44 kHz for standard
Temporal resolution (in seconds)	1

NON-IMAGING SPECIFIC CONSIDERATIONS		
Number of subarrays	1	
Number of tied array beams per subarray	1 VLBI beam for target, at least 7 beams for calibrators.	
Required angular resolution of a tied array beam (arcmin)	0.6 arcsec (15 GHz, 2 cm and 4 km radius subarray)	
Maximum baseline required (km)	8	
Required baseline sensitivity	between SKA1 VLBI beam and a 100m-class dish is ~40 μJy in 1 min, 15 GHz, 1 GHz b/w	
Primary beam size (FWHM, arcmin)	15m antenna 5.3 arcmin (15 GHz, 2cm)	
Total bandwidth for each tied array beam	1 GHz (equivalent to 8 Gbps data rate for 2-bit sampling)	
Number of output channels	5 (200 MHz each centred at the centre frequency of the 256MHz standard channels for the VLBI stations)	
Output bandwidth (minimum and maximum frequency - MHz)	200 MHz per channel	
Required rms (Jy) (if polarisation products required define for each)		
Dynamic range (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

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IMAGING CONSIDERATIONS (CONTINUUM. This includes the specifications for a 'support image' in the case of VLBI observations, for SKA1-mid local interferometer data using coarse VLBI visibilities)		
Required angular resolution (arcmin) (single value or range)	0.6" (in any case, sub-arcsecond is preferred if possible)	
Maximum baseline required (km)	8 km	
Mapped image size (degrees)	standard FoV	
Required pixel resolution (arcseconds)	standard	
Number of output channels	standard	
Output bandwidth (minimum and maximum frequency - MHz)	1 GHz	
Required rms (Jy per beam) (if polarisation products required define for each)	$2.5x10^{-6}$ Jy/beam assuming 4km subarray	
Dynamic range within image (if polarisation products required define for each)	300 –I, 30 –Q/U/V	
Absolute flux scale calibration	X	1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (spectral – multiple channels of narrow bandwidth) N/A		
Required angular resolution (arcmin) (single value or range)		
Maximum baseline required (km)		
Mapped image size (degrees)		
Required pixel resolution (arcseconds)		
Number of image channels		
Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)		
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
		5%
		10%
		20-50%
		n/a

IMAGING CONSIDERATIONS (SKA-VLBI)	
Required angular resolution (arcmin) (single value or range)	~1 mas
Mapped image size (degrees)	
Number of image channels	

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Channel width (kHz)		
Required rms (Jy per beam per channel) (if polarisation products required define for each)	15x10^{-6} Jy/beam	
Dynamic range within image per channel (if polarisation products required define for each)		
Absolute flux scale calibration		1-3%
	X	5%
		10%
		20-50%
		n/a

DATA ANALYSIS	
Procedures required	Requires well established policies on how SKA1-MID will participate in VLBI observations.
Processing considerations (e.g. flag high wind speed data, reprocessing required?)	N/A
Data products	SKA data products will be beam-formed voltage data for SKA-VLBI, and simultaneous SKA1-MID interferometer images from the same subarray. Final SKA-VLBI data products produced by the PI will be high angular resolution maps of the targets, up to sub-arcsec or mas level (depending on observing frequency), and astrometric positions.
Description of pipeline	Standard imaging pipeline for SKA. Standard imaging pipeline for VLBI. Astrometric packages.
Quality assessment plan & cadence	First observe a couple of targets and assess results. Adjust observing strategy if necessary.
Latency (Desired time lag between observation commencement and data being available in the archive. e.g. This could range from 'a few seconds' for transient detections using the fast imaging pipeline, to 'upon completion of scheduling block and pipeline reduction' (approximately 24 hours), to ‘at completion of the full project’.)	No time critical, SDP products should be available coincident with external correlator products, before the next observing epoch takes place (1 month). VLBI voltages need to be sent to the external correlator in a timely manner (1-2 weeks after observation completed).

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ISSUES TO BE DETERMINED/RESOLVED (Here you should include any additional information that needs to be resolved before this science can be carried out)

REFERENCES
Froeschle, M. & Kovalevsky, J. 1982, A&A, 116, 89 Zacharias, N. & Zacharias, M. I. 2014, AJ, 147, 95 Malkin, Z. 2016, MNRAS, 461, 193

ANNEX 2: SKA-VLBI Science Performance

SKA PHASE 1 VLBI SCIENCE PERFORMANCE

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Context .... Operations Planning Group
Revision .... A
Authors .... C. Garcia-Miro, Zsolt Paragi, Antonio Chrysostomou
Date 2019-04-29
Document Classification .... UNRESTRICTED
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A	2019-04-29	-	First draft

DOCUMENT SOFTWARE

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

ORGANISATION DETAILS

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Website	www.skatelescope.org

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LIST OF ABBREVIATIONS

AD .... Applicable Document
BD .... SKA1 Baseline Design
BM .... Beams
B/W .... Bandwidth
CI .... Configuration Item
CSP .... Central Science Processor
DDBH .... Digital Data Back Haul
FWHM .... Full Width Half Maximum
FSP .... Frequency Slice Processor
GBASE .... Gigabit/Second Baseband
GE .... Gigabit Ethernet
HPSO .... High Priority Science Objective
ICD .... Interface Control Document
M&C .... Monitor and Control
NIP .... Non-Image Processing
PSF .... Point Spread Function
RD .... Reference Document
RFI .... Radio Frequency Interference
Rev .... Revision
SADT .... Signal and Data Transport
SAT .... Synchronisation and Timing
SDP .... Science Data Processor
SEFD .... System Equivalent Flux Density
SPC .... Science Processing Centre
SKA .... Square Kilometre Array
SKA1 .... Phase 1 of the SKA
SKA1-LOW .... Low frequency array of dishes of SKA1
SKA1-MID .... Mid frequency array of dishes of SKA1
SKAO .... SKA Organisation
TBC .... To be confirmed
TBD .... To be decided
TM .... Telescope Manager
VLBI .... Very Long Baseline Interferometry

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1 Introduction

1.1 Purpose and Scope of Document

This document summarizes the SKA Phase 1 VLBI capability and the science performance that will be achieved for different VLBI observing configurations.

The SKA1 VLBI science performance is based on the current estimates of the scientific performance anticipated for the SKA1 Design Baseline and described in detail in [AD4]. Calculations are made for the frequency range 50-350 MHz for SKA1-LOW and 350 MHz-50 GHz for SKA1-MID, regardless of the deployment baseline plans for the different SKA1 receivers.

2 Applicable and Reference Documents

2.1 Applicable documents

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

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

[AD2] Design Baseline Description, SKA-TEL-SKO-0000002, Rev 3

[AD3] SKA1 CSP Architectural Design Document, SKA-TEL-CSP-0000014, Rev 5

[AD4] Anticipated SKA1 Science Performance, SKA-TEL-SKO-0000818, Rev 1

[AD5] SKA1 Operational Concept Document, SKA-TEL-SKO-0000307, Rev 3

2.2 Reference documents

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

[RD1]

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3 SKA-VLBI Capability Overview

This section of the document provides an overview of the VLBI capability for the SKA1-MID and LOW telescopes. For a detailed description of the VLBI capability refer to [AD1], [AD2], and [AD3].

The phased-up SKA1 will provide sensitive VLBI beams for Global VLBI observations. There may be multiple beams produced from a single subarray, or from a number of subarrays. The size of the subarrays can be chosen to obtain desired sensitivities and FWHM sizes for the VLBI beams. The VLBI observing mode is considered a standard observing mode of both SKA1-LOW and MID telescopes [AD3].

One particular observing configuration that will be very advantageous for SKA-VLBI science is the production of several VLBI beams from the phased core and the simultaneous production of full scale SKA1 interferometer images.

The participation of SKA1 in Global VLBI observations will provide:

- Independent multi-beam capability.
- Operation of independent subarrays.
- Access to Southern skies and the Galactic Center.
- Boost in sensitivity to the μJy regime for individual targets, and to the mJy level for surveys.
- Superior amplitude and polarization calibration.

The VLBI capability will provide to SKA1 science:

- Images of the sky at a broad range of angular scales.
- High angular resolution to the SKA1 High Priority Science Objectives (Figure 1).
- An independent technique for commissioning tool with early public relations opportunities.
- An enthusiastic user community.

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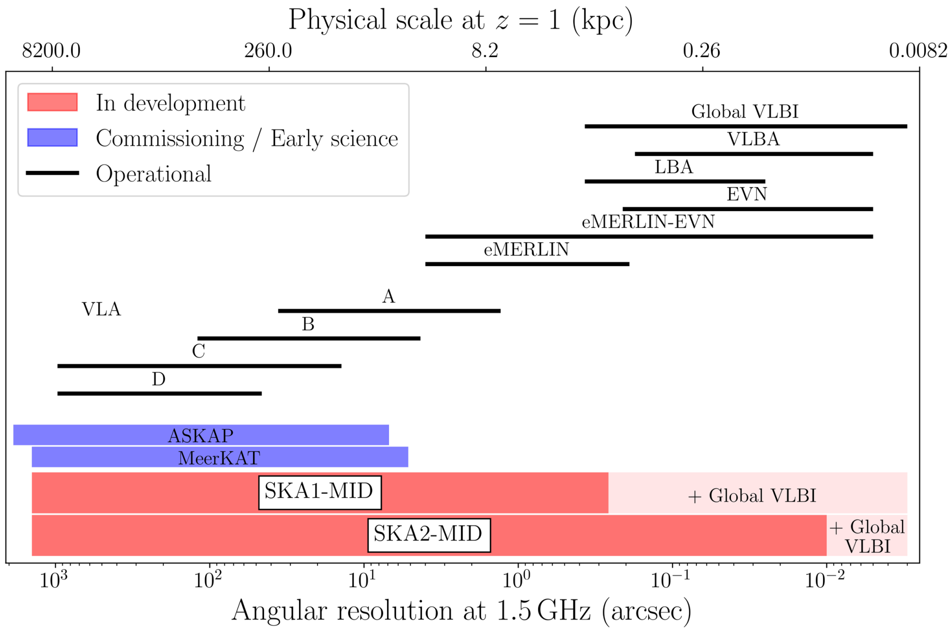

Figure 1. Angular scales probed with SKA-VLBI, Radcliffe (2018). The SKA telescope on its own considerably improves the angular resolution coverage compared with current radio interferometer arrays. When SKA VLBI beams are added to the Global VLBI network the resulting instrument achieves **milli-arcsecond resolutions** or better.

3.1 VLBI Capability for the SKA1-MID telescope

The SKA1-MID correlator in VLBI mode is able to produce at least 4 VLBI beams from one subarray formed from just one antenna or up to the whole array. It also simultaneously provides coarse visibilities from the same subarray that will be processed by the Science Data Processor (SDP) to provide real-time beamforming calibration and corresponding image cubes.

If the SKA1-MID array is divided into more than one subarray, using the same processing resources it can provide at least 4 VLBI beams for each of the defined subarrays.

In summary, the VLBI mode for SKA1-MID telescope provides (Figure 2, [AD3]):

- 4 VLBI beams with 2.5 GHz bandwidth per polarization and per subarray, or more beams can be formed by trading bandwidth (e.g. 10 VLBI beams with 1GHz b/w or a maximum of 52 VLBI beams with 200MHz b/w per subarray).
- Images cubes with 200 kHz frequency resolution, from the same subarray (using coarse VLBI visibilities).

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- Each VLBI beam is channelised in tunable overlapping beam channels with 1, 2, …, 128, 200 MHz b/w; 2, 4,..,16 bits; single/dual polarization. The channels are formatted using VDIF real representation.
- Polarisation correction and RFI flagging and excision is performed in real-time.

To calculate the number of available VLBI beams depending on its bandwidth, one should take into account that each processing unit of the correlator (Frequency Slice Processor, FSP) in VLBI mode provides 2 VLBI beams with 200 MHz bandwidth, and there is a maximum of 26 FSPs available in total for the processing of all the observing modes. For example, for 10 VLBI beams with 1GHz bandwidth, 25 FSPs are needed, and only 1 FSP is left for the other observing modes.

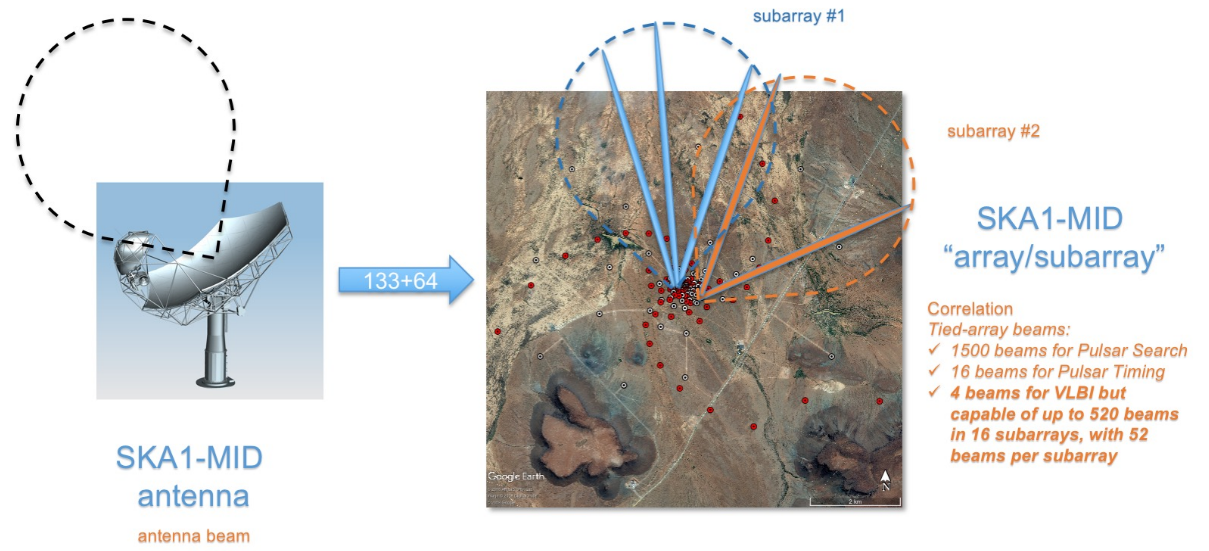

Figure 2. VLBI Capability for SKA1-MID telescope.

The SKA1-MID telescope allows commensal observing of all Imaging and non-Imaging observing modes constraint by the limited processing resources (FSPs available). Table 1 shows different commensal observing possibilities in different observing bands, outlining those configurations where commensal observing is not possible at full bandwidth.

When planning commensal observations, the following rules need to be taken into account to calculate the number of FSPs required for each processing mode:

- VLBI: each FSP in VLBI mode provides 2 VLBI beams with 200 MHz bandwidth. It also provides coarse visibilities with the same bandwidth, with 200 kHz frequency resolution. There is no possibility to trade number of VLBI beams and bandwidth within each FSP.
- Imaging: each FSP in Imaging processes 200 MHz bandwidth for correlation providing visibilities with standard frequency resolution (13.44 kHz).

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- Pulsar Search (PSS): each FSP in PSS mode provides 192 Pulsar Search beams with 300 MHz bandwidth.
- Pulsar Timing (PST): each FSP in PST mode provides one Pulsar Timing beam with 200 MHz bandwidth.
- Zoom windows: each FSP in zoom mode processes 1 zoom window of different sizes (3.125-100 MHz) for correlation, providing visibilities with frequency resolutions up to 191 Hz.

Band	VLBI + coarse Imag	Imaging	PSS	PST	Zoom
Band 1 (0.35-1.05GHz)	4 bm 512 MHz	full b/w	1500 bm 300 MHz	16 bm full b/w	4 windows
	4 bm full b/w (700 MHz)	full b/w	1500 bm 300 MHz	16 bm full b/w	2 windows
	10 bm full b/w	full b/w	384 bm 300 MHz		
			1152 bm 300 MHz		
	12 bm full b/w		384 bm 300 MHz		
Band 2 (0.95-1.76GHz)	4 bm 512 MHz	full b/w	1500 bm 300 MHz	16 bm full b/w	2 windows
	4 bm full b/w (810 MHz)	full b/w	1500 bm 300 MHz	16 bm 600 MHz	
	8 bm full b/w	full b/w	192 bm 300 MHz		
	10 bm full b/w		192 bm 300 MHz		
Band 5a/b (4.6-8.5GHz & 8.3-15.3GHz)	2 bm full b/w (5 GHz)	🚫	🚫	🚫	🚫
	4 bm 2.5 GHz	🚫	🚫	🚫	🚫
	4 bm 512 MHz	512 MHz	1500 bm 300 MHz	16 bm 512 MHz	6 windows
	8 bm 1 GHz	1 GHz	192 bm 300 MHz		
			1152 bm 300 MHz		
	10 bm 1 GHz		192 bm 300 MHz		
	🚫	full b/w	🚫	🚫	🚫

Table 1. Commensal Observing examples with SKA1-MID (bm=beams, b/w=bandwidth).

3.2 VLBI Capability for SKA1-LOW telescope

The SKA1-LOW correlator in VLBI mode is able to produce up to 4 VLBI beams, from one subarray or distributed among different subarrays. The maximum radius that the SKA1-LOW correlator can phase-up is 20 Km.

In summary, the VLBI mode for SKA1-LOW telescope provides (Figure 3):

- Up to 4 VLBI beams with a maximum of 256MHz b/w per polarisation, produced from one subarray or from up to 4 subarrays.

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- Each VLBI beam is channelised in tunable adjacent beam channels with 1, 2, …, 64, MHz b/w; 2 … 8 bits; oversampling, single/dual polarisation. The channels are formatted using VDIF real representation.
- Polarisation correction and RFI flagging and excision is performed in real-time.

The SKA1-LOW correlator architecture is compatible with the production of more VLBI beams, up to 16, but drive additional cost, as an additional VLBI server will be needed for every extra VLBI beam.

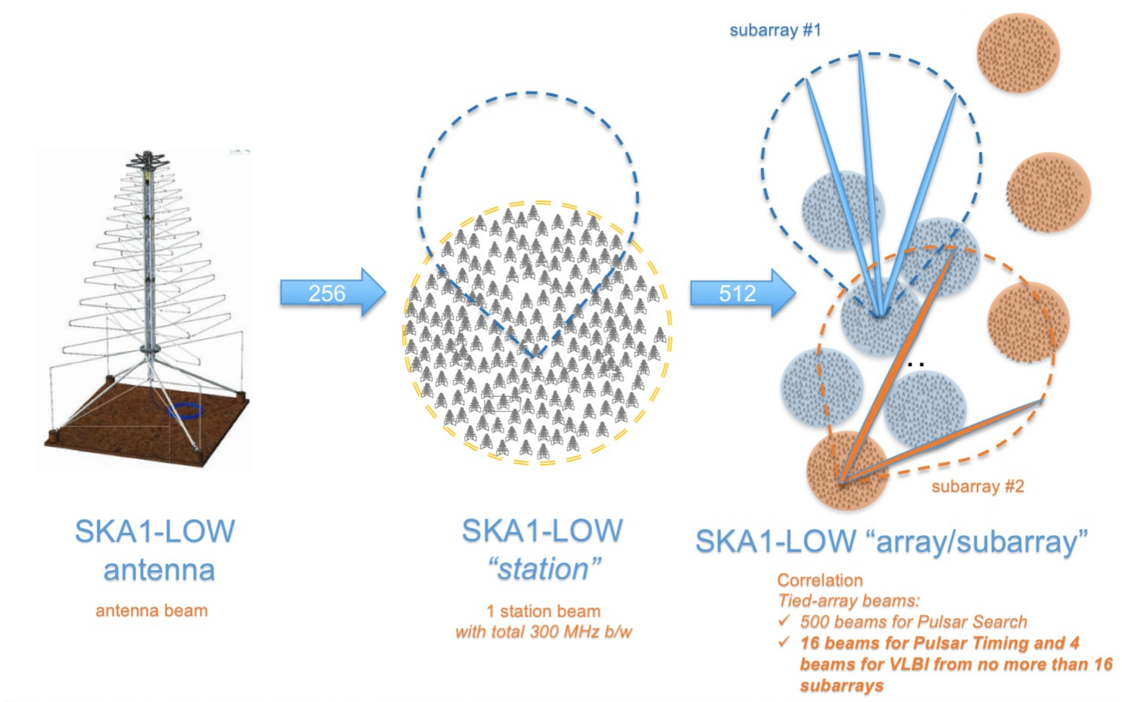

Figure 3. VLBI Capability for SKA1-LOW telescope.

The SKA1-LOW telescope is capable of performing simultaneously all Imaging and non-Imaging observing modes, within each subarray, for up to 16 subarrays.

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4 SKA-VLBI Science Performance

The SKA-VLBI science performance described in this document is based on the current estimates of the scientific performance anticipated for the SKA1 Design Baseline and described in detail in [AD4].

The VLBI baseline sensitivity (or image thermal noise) depends on the SEFD of the antennas that form the baseline (or the array) and the integration time, T_{obs}, and the observing bandwidth, (or a corresponding DATARATE, assuming 2-bit sampling), as follows:

$$\text{NOISE [Jy/beam, 1-sigma]} = \text{SEFD* [Jy]} / (\text{DATARATE}/2 \text{ [bits/s] } T_{obs} \text{ [s]})^{1/2} / \eta \,,$$

(Equation 1)

where,

$$\text{SEFD*} = 1/(\sum_{i,j=1}^{n;i<j} 1/(\text{SEFD}_i * \text{SEFD}_j)^{1/2}$$

and η is the "VLBI efficiency factor", encompassing quantisation losses, bandpass effects, efficiency factors in the VLBI correlator, gain curve reductions away from zenith, etc. For 2-bit sampling, η <= 0.88, and is commonly assumed to be 0.7 for current arrays.

The following sections explain the calculations necessary to compute the SEFD for SKA1-MID and LOW VLBI beams for different subarray configurations and observing frequencies. The baseline sensitivities have been calculated assuming a 100m class remote telescope, with characteristics detailed in the EVN status tables (http://old.evlbi.org/user_guide/EVNstatus.txt).

Appendices A and B contain SKA1-MID and LOW science performance numeric tables for the usual VLBI bands, including the collecting area for each VLBI subarray configuration, VLBI beam FWHM and SEFD, and baseline sensitivities.

4.1 VLBI Science Performance for SKA1-MID telescope

The sensitivity of a single dish can be expressed as the effective collecting area, A_{eff}, divided by the total system temperature, T_{sys}.

In particular the effective collecting area of the SKA1 and MeerKAT dishes is plotted in Figure 4 (left and right). This effective collecting area can be expressed as, $A_{eff} = A_{phys}\,\eta_A$, the product of the physical antenna aperture with an aperture efficiency, η_A, that takes into

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account feed illumination efficiency, phase efficiency of the reflector surface, and diffractive losses at the lowest frequencies. For detailed calculations of these coefficients refer to [AD4].

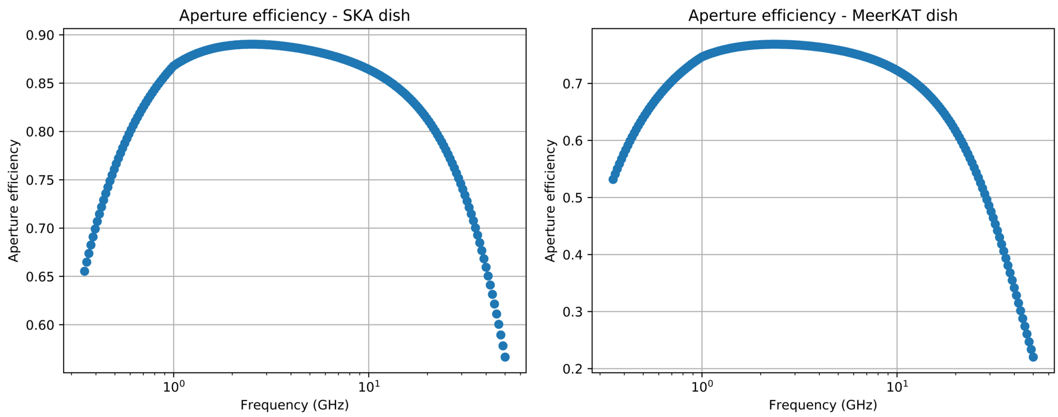

Figure 4. Effective collecting area and aperture efficiency for an SKA1 dish (left) and MeerKAT dish (right).

The system temperature can be expressed approximately as,

$T_{sys} = (T_{rcv} + T_{spl} + T_{sky})_x/\exp[-\tau_0 \sec(z)]$,

in terms of the receiver temperature, T_{rcv}, the spill-over temperature, T_{spl}, the sky temperature, T_{sky}, the atmospheric zenith opacity, τ_0, and the zenith angle, z. The subscript "x" is used to indicate that a correction of the form $T_x = T\,\{(h\nu/kT)/[\exp(h\nu/kT) - 1]\}$ is applied.

The sky temperature is the sum of CMB, Galactic and atmospheric contributions. The different terms are explained in detail at [AD4]. Figure 5 and Figure 6 shows the system temperatures at zenith for the SKA1 and MeerKAT dishes, for best observing conditions (5mm precipitable water vapour for dry conditions and 10th percentile of the Galactic foreground contribution) and worst observing conditions (20mm precipitable water vapour for wet conditions and 90th percentile of the Galactic foreground contribution).

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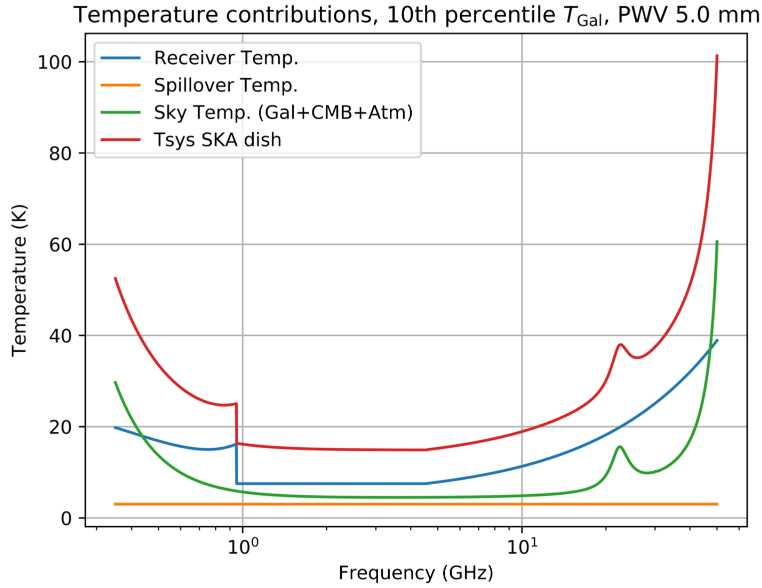

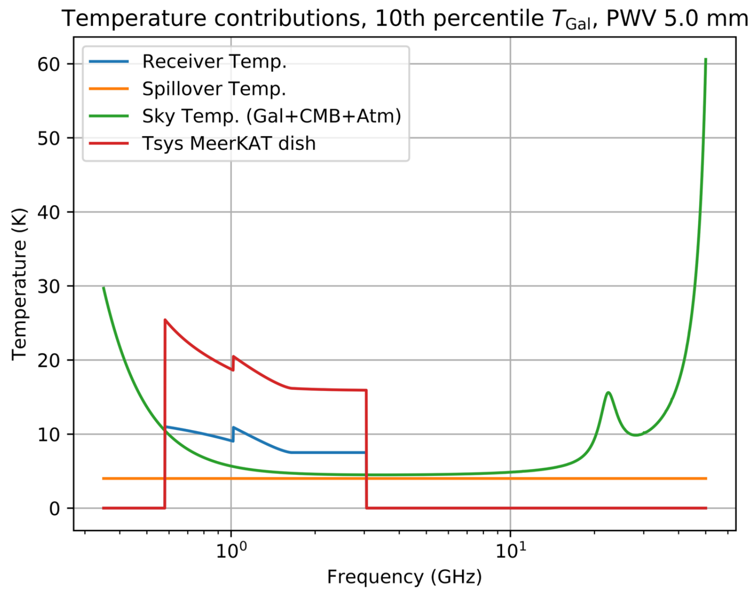

Figure 5. System temperature for an SKA1 dish (top) and MeerKAT dish (bottom), for best observing conditions at zenith.

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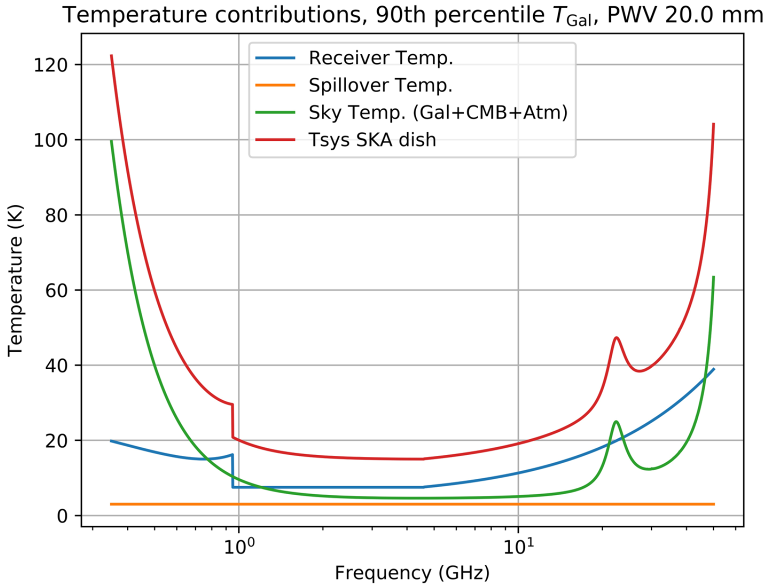

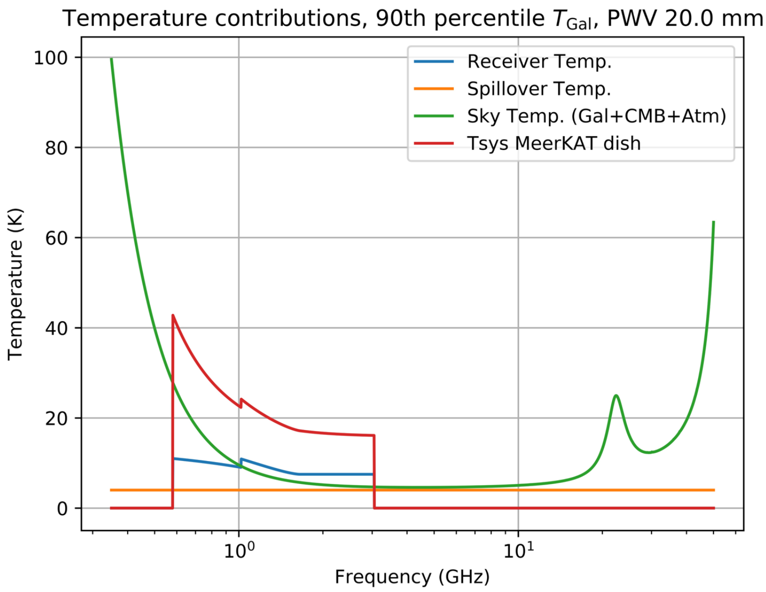

Figure 6. System temperature for an SKA1 dish (top) and MeerKAT dish (bottom), for worst observing conditions at zenith.

Figure 7 shows the sensitivity or gain of a single SKA1 dish (blue) and a single MeerKAT dish (orange), in terms of the effective collecting area, A_{eff}, and the total system temperature, T_{sys} (left) and the SEFD (in Jy) calculated from it (right), assuming best observing conditions at zenith. Results in Figure 7 (left) for a SKA1 dish are equivalent to the ones shown in [AD4], Figure 4 and Table 4.

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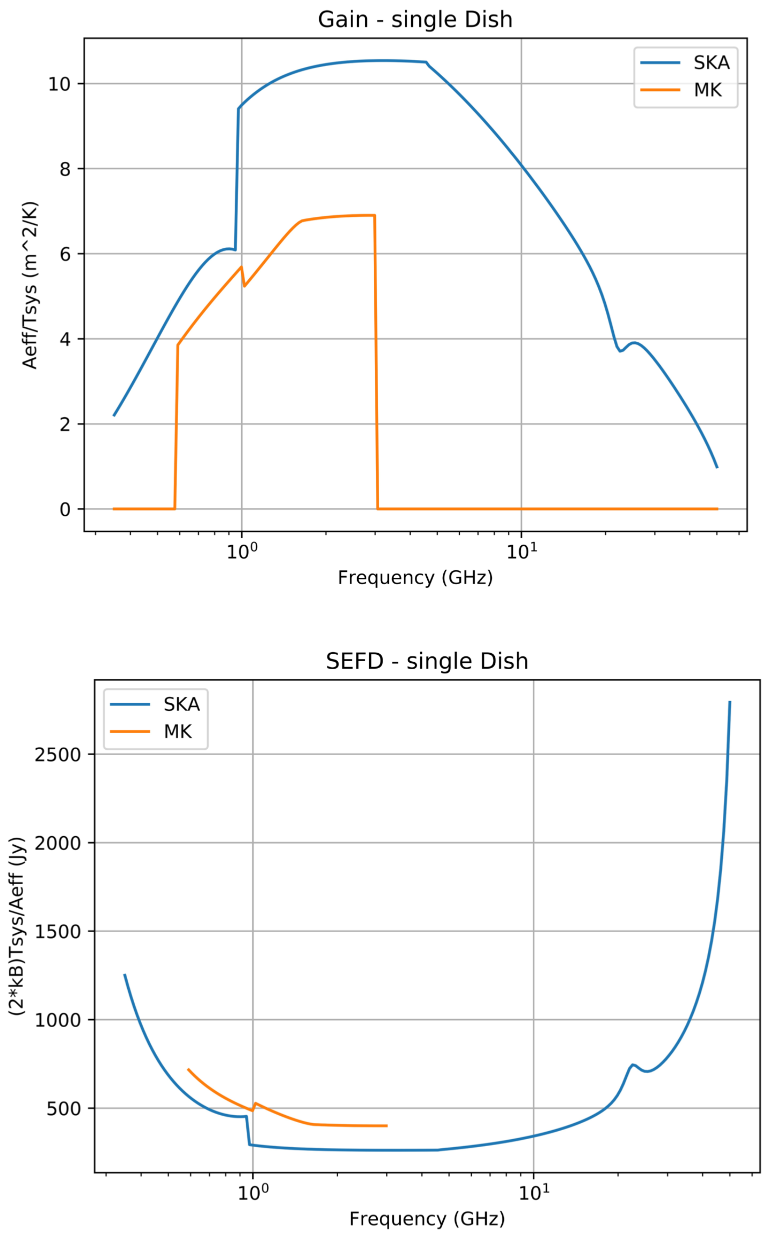

Figure 7. Single dish Gain (top) and SEFD (bottom) for an SKA1 dish (blue) and for a MeerKAT dish (orange), for best observing conditions at zenith.

Once the single dish gains are modelled, one can calculate the combined sensitivity and SEFD for different SKA1-MID subarrays or the whole array, including both the 133 SKA1 15m dishes as well as the 64 MeerKat 13.5m dishes. Note that the MeerKAT dishes are only assumed to contribute in the UHF (900 MHz), L (1.6 GHz) and S (2 GHz) bands. Figure 8 shows the combined sensitivity of the full array (left) and the SEFD (right), specifying the values for SKA1 and MeerKAT only arrays, assuming best observing conditions at zenith.

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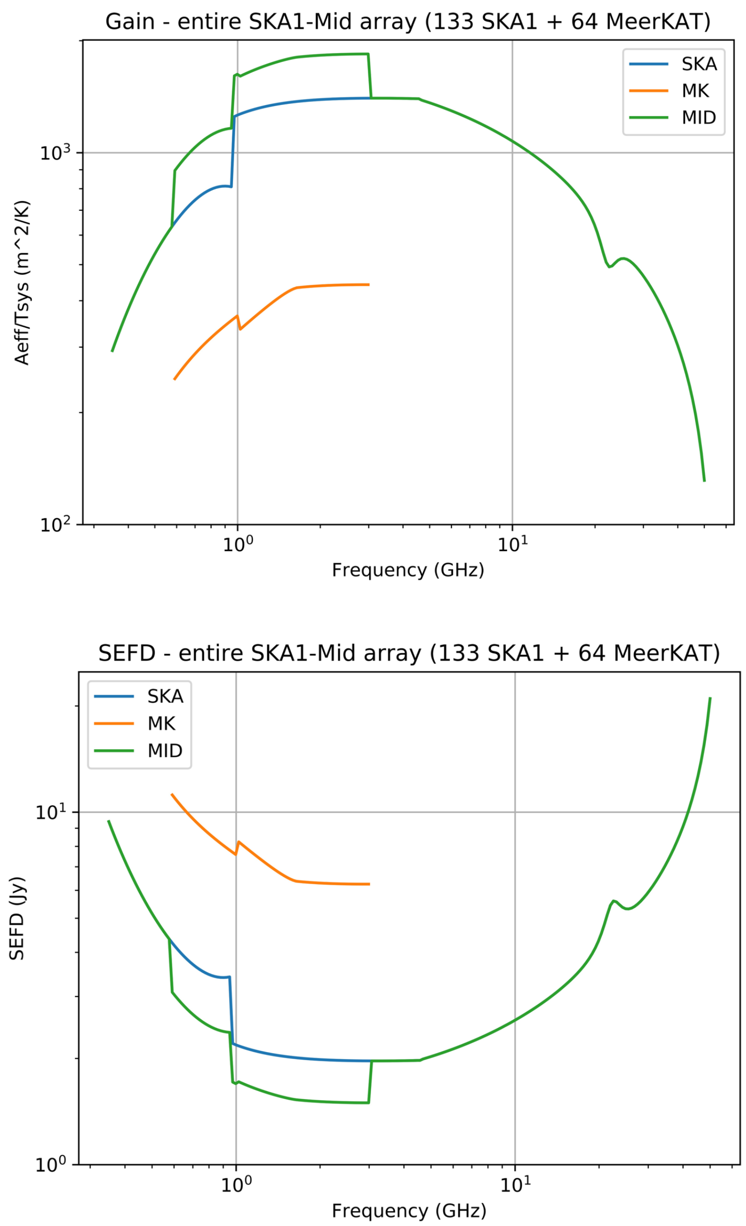

Figure 8. Full array Gain (left) and SEFD (right), for best observing conditions at zenith.

VLBI beams are produced by coherently phasing up a subarray of SKA1-MID antennas. If the MID array is divided in more than one subarray, VLBI beams can be produced from each of the subarrays. In this study we have assumed that the VLBI beams are produced from just one circular subarray, centred at the centre of the array, of different radii. Other configurations are possible, as long as the subarrays are exclusive, i.e. one individual antenna cannot belong to more than one subarray at a time. Figure 9 shows different possibilities for subarrays configurations to produce VLBI beams, with radius 4 km and 75% of the total collecting area, 20 km and 87% of the total collecting area or containing the full

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array. The subarray chosen will be in terms of the sensitivity and resolution needed in the VLBI beams.

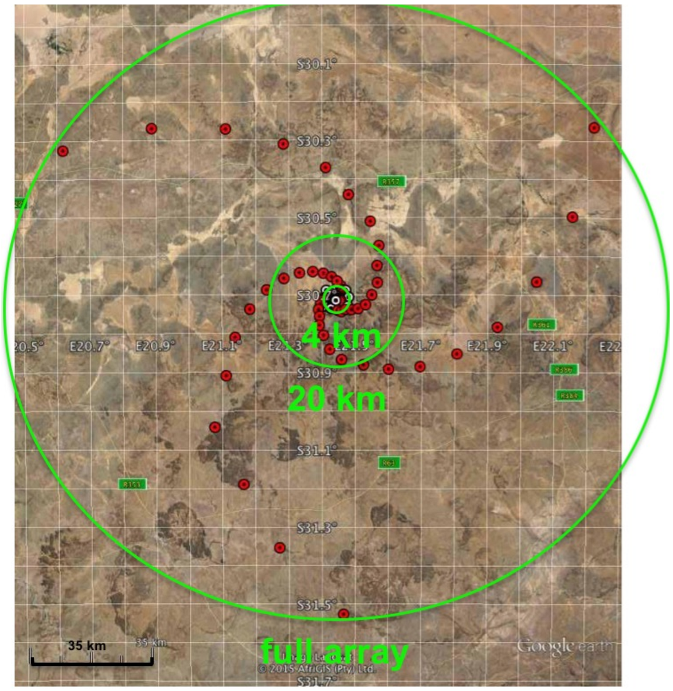

Figure 9. Different SKA-VLBI configurations for SKA1-MID.

The SEFD for the different VLBI subarrays configurations plotted in Figure 9 are shown in Figure 10, comparing the best and worst observing conditions, detailed previously.

Baseline sensitivities for an SKA1-MID VLBI beam and a 100m class telescope have been calculated using (Equation 1, assuming different observing bandwidths and 60sec integration times (Figure 11).

Appendix A contains SKA1-MID science performance numeric tables for the usual VLBI bands, including the collecting area for each VLBI subarray configuration, VLBI beam FWHM and SEFD, and baseline sensitivities.

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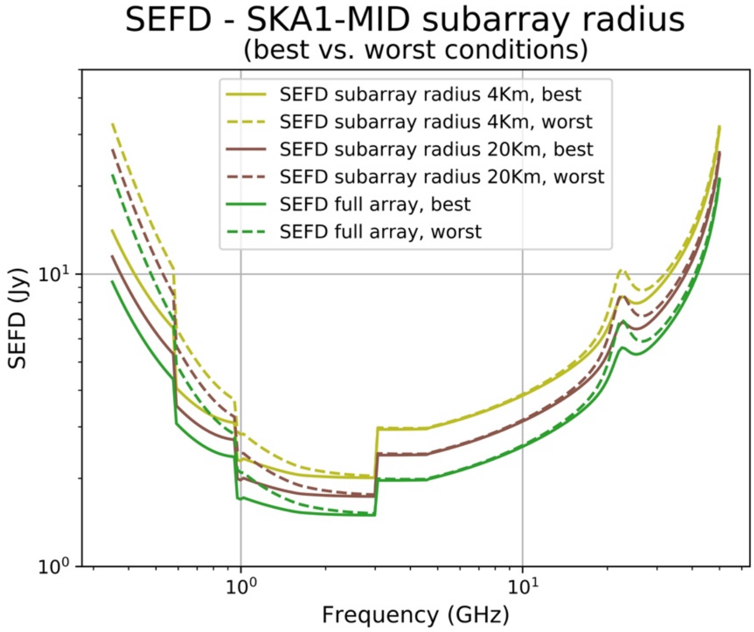

Figure 10. SEFD for different VLBI subarrays configurations, for best (solid line) and worst (dashed line) observing conditions at zenith.

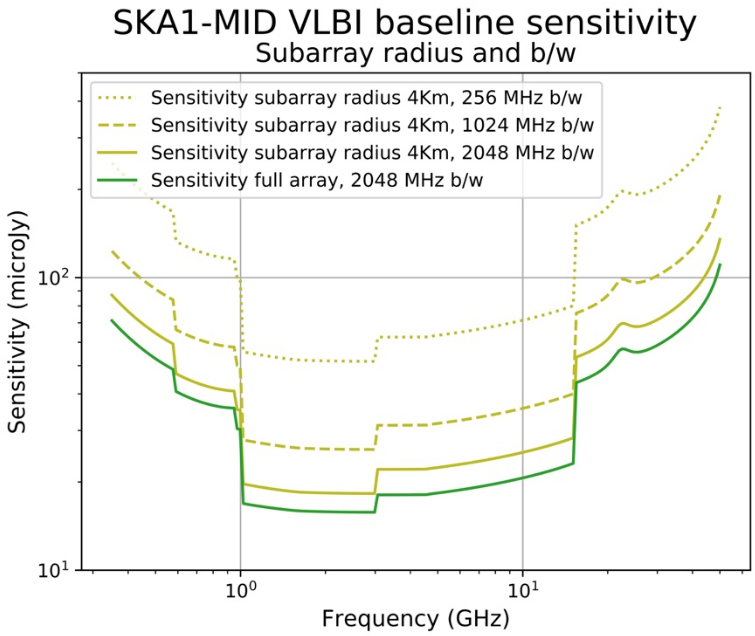

Figure 11. Baseline sensitivity for different SKA1-MID subarrays configurations and a 100m class remote telescope, for different observing bandwidths and 60sec integration times, for best observing conditions at zenith.

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4.2 VLBI Science Performance for SKA1-LOW telescope

The SKA1-LOW array will be arranged in groups, or stations, of 256 log-periodic antennas distributed randomly in 38m diameter areas. The sensitivity of every station has been modelled and is documented in [AD4], Table 3. Figure 12 shows the station sensitivity (left) and the SEFD values (right) in terms of the observing frequency, corrected for the zenith direction, with an assumed Galactic foreground between the 10th and 50th percentile of the all-sky distribution and would apply to directions well away from the Galactic plane.

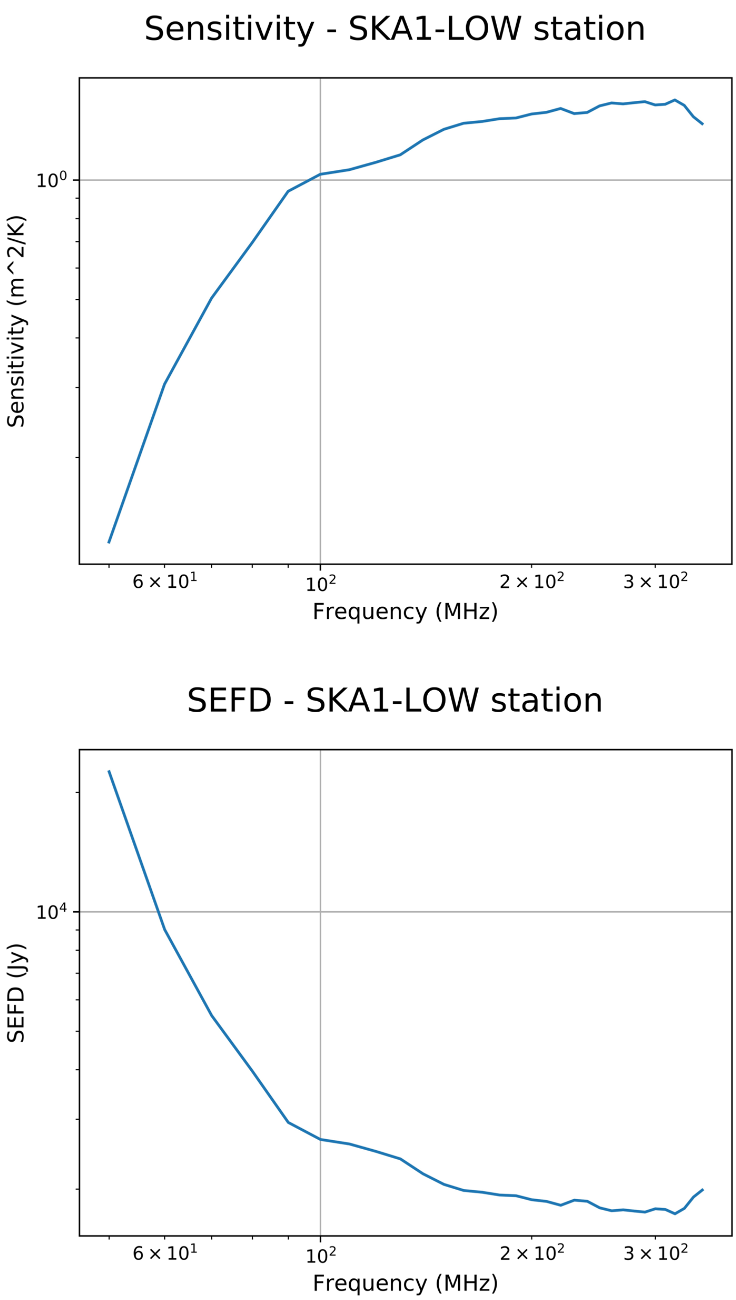

Figure 12. Single SKA1-LOW station sensitivity (top) and SEFD (bottom), at zenith.

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The combined sensitivity for the whole SKA1-LOW array is plotted in Figure 13.

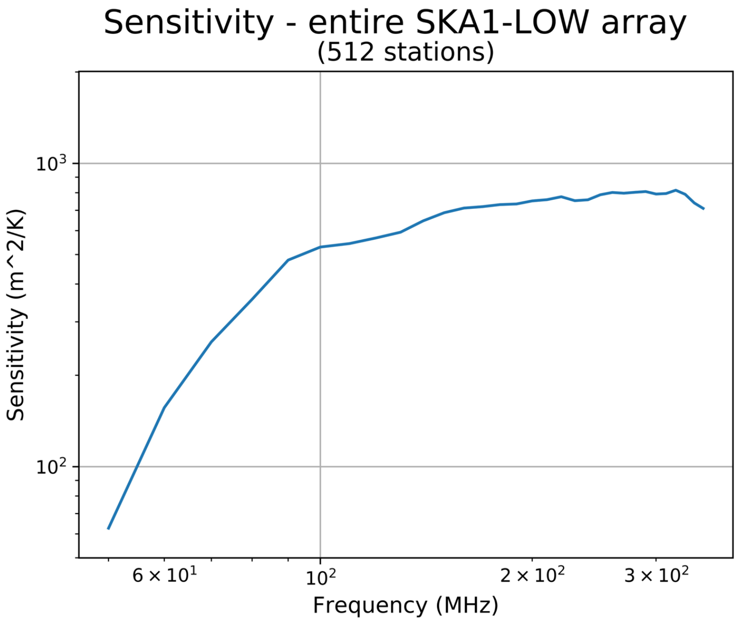

Figure 13. Full SKA1-LOW array sensitivity, at zenith.

For VLBI with SKA1-LOW, VLBI beams are produced from either one subarray, or from different subarrays with the caveat that the beams (a maximum of 4) are shared amongst the subarrays. For example, for 4 subarrays, one VLBI beam is produced for each, for 2 subarrays, two VLBI beams (or 1 and 3) are produced for each. Another caveat is that SKA1-LOW correlator cannot phase-up subarrays with baselines longer than 40 km.

In this study we have assumed that the VLBI beams are produced from just one circular subarray, centred at the centre of the array, that could have different radii, up to 20 km, although other configurations are possible. Figure 14 shows different possibilities for subarray configurations to produce VLBI beams, with radius 4 km and 68% of the total collecting area and 20 km and 90% of the total collecting area. The subarray chosen will be in terms of the sensitivity and resolution needed in the VLBI beams.

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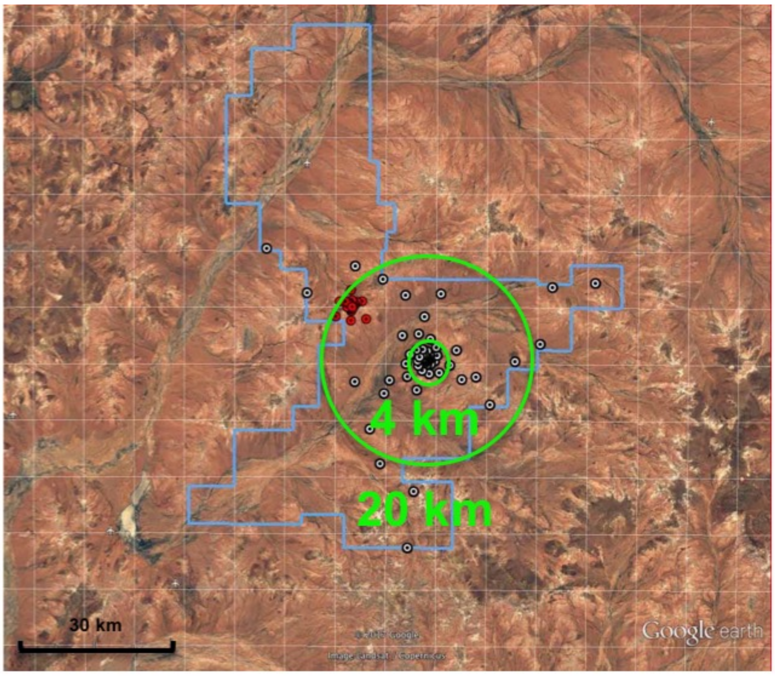

Figure 14. Different SKA-VLBI configurations for SKA1-LOW.

The SEFD for the different VLBI subarrays configurations plotted in Figure 14 are shown in Figure 15.

Baseline sensitivities for an SKA1-LOW VLBI beam and a 100m class telescope have been calculated using (Equation 1, assuming different observing bandwidths and 60sec integration time (Figure 16).

Appendix B contains SKA1-LOW science performance numeric table for the VHF band, including the collecting area for each VLBI subarray configuration, VLBI beam FWHM and SEFD, and baseline sensitivities.

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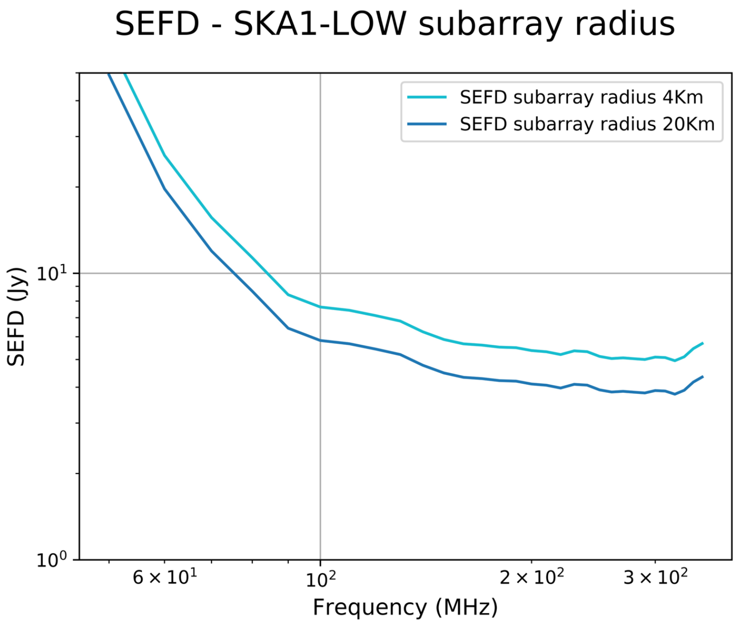

Figure 15. SEFD for different SKA1-LOW subarrays configurations, at zenith.

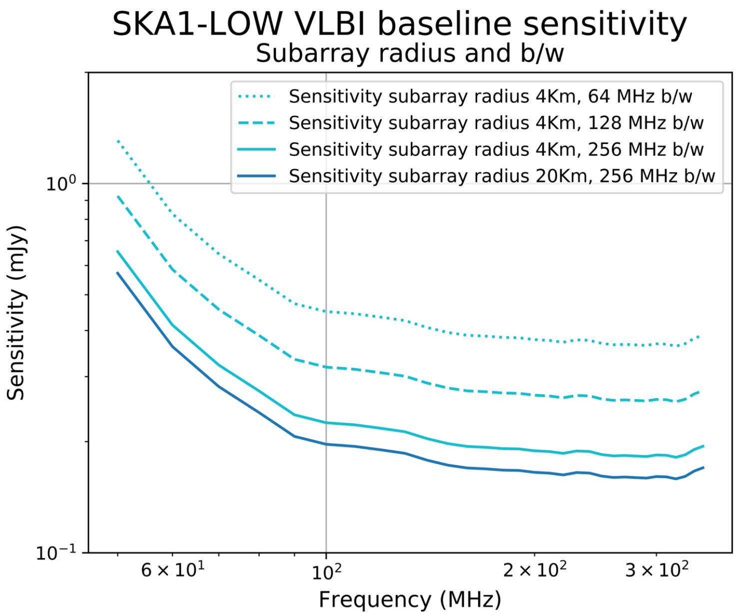

Figure 16. Baseline sensitivity for different SKA1-LOW subarrays configurations and a 100m class remote telescope, at zenith.

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APPENDIX A. VLBI Performance Tables for SKA1-MID

Band	SKA-core radius (Km)	Collecting area (%)	VLBI beam FWHM (arcsec)	VLBI beam SEFD (Jy)	Bandwidth (MHz)	Remote tel. SEFD (Jy)	Baseline sensitivity 60s (μJy)
UHF-band 30 cm (SKA Band 1 0.35-1.05 GHz, CF 900 MHz)	1	57.5	35.6	4.1	256/512/700	65	133.1/94.1/80.5
	4	74.9	9	3.1	256/512/700	65	115.7/81.8/70.0
	20	86.5	1.8	2.7	256/512/700	65	108.0/76.4/65.3
	full array	100	0.5	2.4	256/512/700	65	101.8/72.0/61.6

Table 2. UHF-Band VLBI science performance with SKA1-MID.

Band	SKA-core radius (Km)	Collecting area (%)	VLBI beam FWHM (arcsec)	VLBI beam SEFD (Jy)	Bandwidth (MHz)	Remote tel. SEFD (Jy)	Baseline sensitivity 60s (μJy)
L-band 21/18 cm (SKA Band 2 0.95-1.76 GHz, CF 1.6 GHz)	1	57.5	21.4	2.7	256/512/810	20	59.8/42.4/33.7
	4	74.9	5.4	2.1	256/512/810	20	52.8/37.4/29.7
	20	86.5	1.1	1.8	256/512/810	20	48.9/34.6/27.5
	full array	100	0.3	1.5	256/512/810	20	44.6/31.6/25.1

Table 3. L-Band VLBI science performance with SKA1-MID.

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Band	SKA-core radius (Km)	Collecting area (%)	VLBI beam FWHM (arcsec)	VLBI beam SEFD (Jy)	Bandwidth (MHz)	Remote tel. SEFD (Jy)	Baseline sensitivity 60s (μJy)
C-band 6/5 cm (SKA Band 5a 4.6-8.5 GHz, CFs 5 GHz & 6 GHz)	1	52.6	7.1 5.9	3.8 4.1	256/512/1024	20 25	71.1/50.2/35.5 82.5/58.3/41.3
	4	67	1.8 1.5	3.0 3.2	256/512/1024	20 25	63.1/44.6/31.6 72.9/51.6/36.5
	4 50% receivers	35.5	1.8 1.5	6.0 6.4	256/512/1024	20 25	89.3/63.1/44.6 103.1/72.9/51.6
	20	82	0.4 0.3	2.5 2.6	256/512/1024	20 25	57.6/40.8/28.8 65.7/46.5/32.9
	full array	100	0.1 0.08	2.0 2.1	256/512/1024	20 25	51.5/36.5/25.8 59/41.8/29.5
	full array 50% receivers	50	0.1 0.08	4.0 4.2	256/512/1024	20 25	72.9/51.6/36.5 83.5/59.1/41.8

Table 4. C-Band VLBI science performance with SKA1-MID.

Band	SKA-core radius (Km)	Collecting area (%)	VLBI beam FWHM (arcsec)	VLBI beam SEFD (Jy)	Bandwidth (MHz)	Remote tel. SEFD (Jy)	Baseline sensitivity 60s (μJy)
X-band 3.6 cm (SKA Band 5b 8.3-15.3 GHz, CF 8.4 GHz)	1	52.6	4.3	4.5	256/512/1024	20	77.3/54.7/38.7
	4	67	1.1	3.6	256/512/1024	20	69.2/48.9/34.6
	4 50% receivers	35.5	1.1	7.2	256/512/1024	20	97.8/69.2/48.9
	20	82	0.2	2.9	256/512/1024	20	62.1/43.9/31.0
	full array	100	0.06	2.4	256/512/1024	20	56.5/39.9/28.2
	full 50% receivers	50	0.06	4.8	256/512/1024	20	79.9/56.5/39.9

Table 5. X-Band VLBI science performance with SKA1-MID.

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Band	SKA-core radius (Km)	Collecting area (%)	VLBI beam FWHM (arcsec)	VLBI beam SEFD (Jy)	Bandwidth (MHz)	Remote tel. SEFD (Jy)	Baseline sensitivity 60s (μJy)
K-band 1.3 cm (SKA Band 6, CF 23 GHz)	1	52.6	1.5	10.6	256/512/1024	70	222.0/157.0/111.0
	4	67	0.4	8.3	256/512/1024	70	196.5/138.9/98.2
	4 50% receivers	35.5	0.4	16.6	256/512/1024	70	277.8/196.5/138.9
	20	82	0.08	6.8	256/512/1024	70	177.8/125.7/88.9
	full array	100	0.02	5.5	256/512/1024	70	159.9/113.1/80.0
	full array 50% receivers	50	0.02	11.0	256/512/1024	70	226.2/159.9/113.1

Table 6. K-Band VLBI science performance with SKA1-MID.

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APPENDIX B. VLBI Performance Tables for SKA1-LOW

Band	SKA-core radius (Km)	Collecting area (%)	VLBI beam FWHM (arcsec)	VLBI beam SEFD (Jy)	Bandwidth (MHz)	Remote tel. SEFD (Jy)	Baseline sensitivity 60s (μJy)
VHF-band 600-86 cm (SKA LOW Band 50-350 MHz)	1	50.8	713 102	86.7 7.7	64/128/256	100	1518/1073/759 451/319/226
	4	68.4	178 25.5	64.4 5.7	64/128/256	100	1308/925/654 389/275/194
	20	89.5	35.6 5.1	49.2 4.3	64/128/256	100	1144/809/572 340/240/170

Table 7. VHF-Band VLBI science performance with SKA1-LOW.

ANNEX 3: SKA-VLBI Capability paper

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PROCEEDINGS OF SCIENCE

High sensitivity VLBI with SKA

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The Square Kilometre Array (SKA), with the aim of achieving a collecting area of one square kilometre, will be the world's largest radio telescope. A scientific collaboration between 12 countries (with more to join), it will consist of one Observatory with 2 telescopes located in South Africa and Australia. The telescope deployment is planned in two phases, but even in its first stage (SKA1) it will already enable transformational science in a broad range of scientific objectives. The inclusion of SKA1 in the Global VLBI networks (SKA-VLBI) will provide access to very high angular resolution to SKA science programmes in anticipation of the science to be realized with the full telescope deployment (SKA2). This contribution provides an overview of the SKA Observatory VLBI capability, the key operational concepts and outlines the need to update the science use cases.

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

*Speaker.

https://pos.sissa.it/

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1. The Square Kilometre Array

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

Due to the magnitude of the project it is planned to be deployed in two phases. The design of the first phase, SKA1, is supported by a broad international collaboration organised into different Consortia, each responsible for the design of a distinctive component or element of the telescopes, e.g. dishes, correlator, signal and data transport, etc. (see Fig. 1). At the time of writing, this design is being finalised with the Critical Design Reviews (CDRs) of the different elements, and nearing completion. Once the elements' designs have been evaluated and closed-out, the Consortia dissolve and a Bridging Phase starts with support from the former participant institutions. The Bridging Phase prepares for a System Level Critical Design Review to assess the design of the full SKA1 Observatory, and leads towards construction.

2. Implementing VLBI at the SKA1

Comparing to existing radio interferometers, the SKA telescopes will access a wide range of angular resolutions. In its initial phase, SKA1 will greatly surpass the capability of currently operational, connected interferometers in terms of sensitivity, survey speed and sub-arcsecond angular resolution. But in terms of the latter, there are science cases that would benefit from resolutions that are not achievable with connected-element interferometers. Nowadays the highest angular resolutions are achieved by Global VLBI observations, which use coordinated networks of radio telescopes located around the globe and in space, to synthesise an equivalent Earth size instrument or even larger. Inclusion of SKA1 in the Global VLBI networks (SKA-VLBI) will provide multi-beam capability with μJy sensitivity in N-S baselines with access to the Southern Hemisphere and simultaneous images of the sky at a broad range of angular resolutions, down to sub-milliarcseconds for the higher observing frequencies of the SKA ([1], and references therein). The boost in sensitivity will allow efficient VLBI surveys of the sub-mJy source population and access to the μJy regime for individual sources, with improved fidelity due to the SKA superior amplitude and polarization calibration. The multi-beam capability will enable high precision astrometry and enhanced phase referencing techniques, transient localisation, etc.

The Horizon 2020 JUMPING JIVE project recognised the scientific relevance of the SKA-VLBI. It has a devoted work package, "VLBI with SKA", to focus on the definition of a SKA-VLBI Operational Model, define VLBI interfaces and requirements for the SKA, and to help the community develop Science Use Cases for SKA-VLBI and strategies for possible future SKA-VLBI Key Science Projects (KSPs) [2]. It will provide four main deliverables, scheduled in a period of 42 months. This contribution summarises the outcomes of the first deliverable "Details on VLBI Interfaces to SKA Consortia". This consists of a description of the VLBI element that

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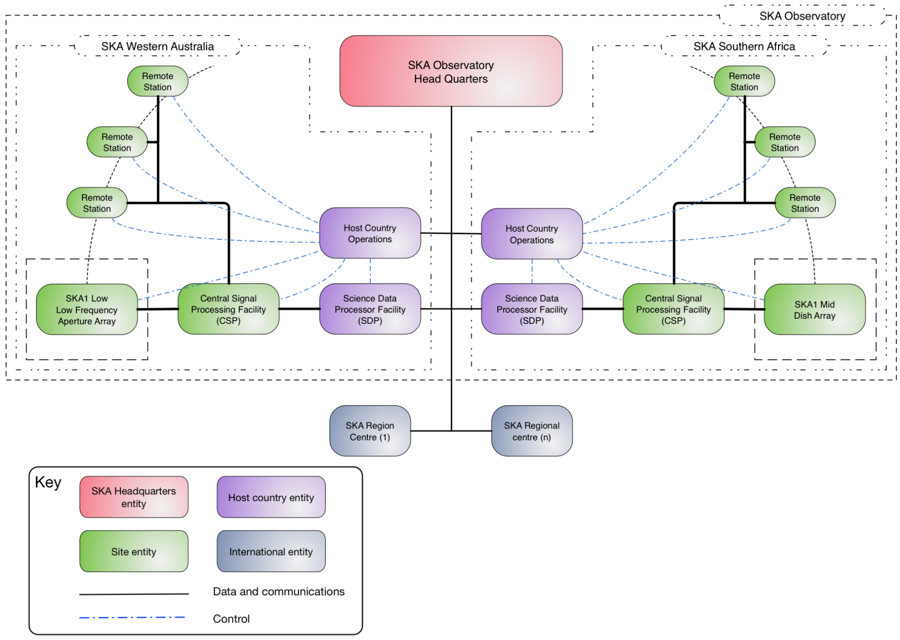

Figure 1: A schematic of the SKA Observatory structure.

will provide the buffering and streaming capability to send SKA VLBI data to an external VLBI correlator, as well as all necessary interfaces for scheduling and conducting VLBI observations with the SKA.

3. SKA-VLBI Capability

VLBI will be an observing mode of the SKA Observatory with the aim of including the participation of the SKA1 LOW and MID telescopes in Global VLBI observations. In this mode, SKA1 provides multiple sensitive VLBI tied-array beams for inclusion in VLBI observations. Each SKA1 VLBI beam acts as an individual element in the VLBI network, equivalent to an individual single beam radio telescope participating in the observation. Tied-array beams are produced by a beamformer in the SKA correlator. Each tied-array beam is formed within a subset (or subarray) of LOW stations or MID dishes by coherently combining the signals from the receptors, such that the combined gain is directed at a specified point on the sky. At least 4 dual-polarisation VLBI beams are formed from one or more subarrays, compatible with the standard VLBI observing mode. The SKA Observatory Data Products for this mode are: VLBI voltage beams formatted into VDIF

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(VLBI standard for data interchange format) packets to be correlated at an External Correlator, associated metadata, and image cubes produced by the Science Data Processor (SDP) from the same subarray from which the VLBI beams were formed. These simultaneous images will be used to calibrate the VLBI data, as well as to complement the science data return by providing images of the sky with different bandwidths and angular and spectral resolutions.

The key operational concepts of the SKA Observatory [3] that define how the VLBI operations will be performed are (i) the ability to configure and simultaneously operate independent subarrays, (ii) the simultaneity of Imaging and VLBI observing modes in the same subarray for calibration and commensal science and (iii) the independent multi-beam capability for each subarray. The VLBI Operational workflow will be as follows (Fig. 2):

- Approved observing proposals become Observatory Projects. The PI will provide all necessary information for the observation design, in particular the VEX file (version 2.0) that describes all the details needed to perform the VLBI observation and to correlate it. With this information the observation is planned and scheduled, and a Scheduling Block (SB) is generated for observation execution. These functions are performed by the Telescope Manager (TM) element.

- Digitised signals from the receivers (LOW log-periodic antennas, or MID dishes) are fed into the Correlator BeamFormers (CBF) of the Central Signal Processor (CSP), located at each SKA1 telescope site. Apart from complex correlation, the correlators form tied-array beams for VLBI, Pulsar Timing and Pulsar Search. The VLBI beams are corrected for polarization impurity, channelized in real representation, and formatted into VDIF packets. Channels that are adversely affected by RFI are either excised or flagged accordingly.

- VLBI VDIF packets are sent to the VLBI Terminal located at the Science Processing Centre (SPC) for either real-time streaming to the External correlator (e-VLBI mode) or for recording (buffering) and streaming after the observation has completed. The e-VLBI mode has several advantages over the recorded mode, such as real-time fringe verification and troubleshooting, fast scientific turnaround, observing configuration adaptability, etc. The VLBI Terminal has access to the Observatory metadata via subscription to the TM element to generate an observing log in support for the external correlation and imaging post-processing calibration.

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

- In parallel, the Signal and Data Transport (SaDT) element is responsible for the science data and non-science data communications links, that route VLBI data to the VLBI Terminal

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from the correlators and connect with TM for monitor and control tasks. The SaDT element is also responsible for the realisation of the SKA timescale based on the use of hydrogen masers which provide a phase-coherent reference signal with the stability required by VLBI.

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

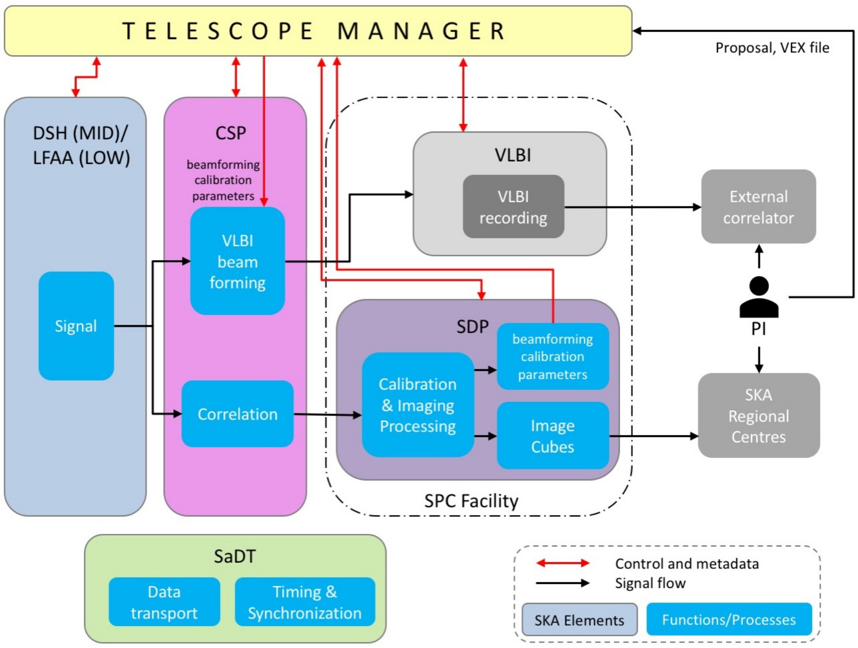

Figure 2: VLBI capability integration in the SKA1 Observatory for LOW and MID telescopes.

3.1 VLBI with the SKA1-MID

The SKA1-MID correlator and beamformer design presents a FX-type FPGA based correlator with a very flexible architecture that efficiently manages its processing resources [4]. It is able to simultaneously process up to 16 independent subarrays, as well as all observing modes simultaneously within each subarray. To do so requires a bandwidth sacrifice, especially for Band 5 (4.6-15.3 GHz). The architecture allows input from 200 antennas separated by several 1000s km and can be

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easily upgraded to support 20% more antennas. The input signal from the different observing bands is divided into 200 MHz frequency chunks, called Frequency Slices, with each slice processed by a Frequency Slice Processor (FSP) - a set of FPGAs configured to perform correlation or the different types of tied-array beamforming. The MID correlator is required to form, in different directions on the sky, 1500 beams for Pulsar Search (PSS), 16 beams for Pulsar Timing (PST) and 4 beams for VLBI. The beams can be produced from the same subarray or distributed amongst different subarrays.

The VLBI beams can be formed using different subarray sizes, up to the full telescope array, with the caveat that longer baselines will suffer from coherence losses and the beams will provide limited FoV. The VLBI capability of MID surpasses that in the System Level 1 requirements [5], by providing a total of 520 VLBI beams of 200 MHz effective bandwidth in dual polarisation from a total of 16 subarrays. Each subarray can produce a maximum of 52 beams of 200 MHz effective bandwidth, or a lesser number of beams but with larger bandwidths, e.g. 4 beams of 2.5 GHz bandwidth in dual polarisation (Fig. 3).

At the 200 MHz level the RFI contamination is flagged or excised if present and polarisation leakage is corrected. Each 200 MHz frequency slice is channelised in up to 4 dual polarisation beam channels (i.e. subbands in VLBI jargon), with a tunable centre frequency, and bandwidths ranging from 1 to 128 MHz and up to the full 200 MHz bandwidth. Digitisation uses 2 to 16 bits per sample with Nyquist sampling. Beam channels are formatted in VDIF packets using real representation, that are streamed to the VLBI terminal. Power levels in the beam channels and beamforming weights are provided as part of the metadata. Together with VLBI beams, the MID correlator provides visibility data at reduced spectral resolution compared to normal imaging visibilities, to provide calibration solutions to establish beam coherence and for imaging products in support of VLBI calibration.

The MID correlator initial deployment will provide enough processing resources to be able to process the full 5 GHz instantaneous Band 5 bandwidth for just one processing mode at a time. For example for full bandwidth imaging in Band 5, all 26 available FSPs are required. Full simultaneity (commensality) of the different observing modes is achieved in all bands for each subarray for moderate observing bandwidths (Fig. 4).

3.2 VLBI with the SKA1-LOW

The SKA1-LOW correlator and beamformer design also presents an FX-type FPGA based correlator. The correlator is not limited by processing resources as the bandwidth to be processed is much narrower (300 MHz bandwidth between 50-350 MHz) [4]. The resources required are available to provide all different processing modes, Imaging and tied-array beamforming, for each subarray simultaneously, for up to 16 independent subarrays.

The LOW correlator is required to form, in independent directions, 500 beams for the Pulsar Search (PSS), 16 beams for Pulsar Timing (PST) and 4 beams for VLBI. The beams can be produced from the same subarray or distributed amongst different subarrays (Fig. 5). The maximum subarray size for tied-array beamforming is up to 20 km in diameter. The beamforming process for PST and VLBI beams is exactly the same, sharing the resources for up to 16 beams. In principle VLBI requires the use of 4 PST beams but it could process more if they are not used by PST.

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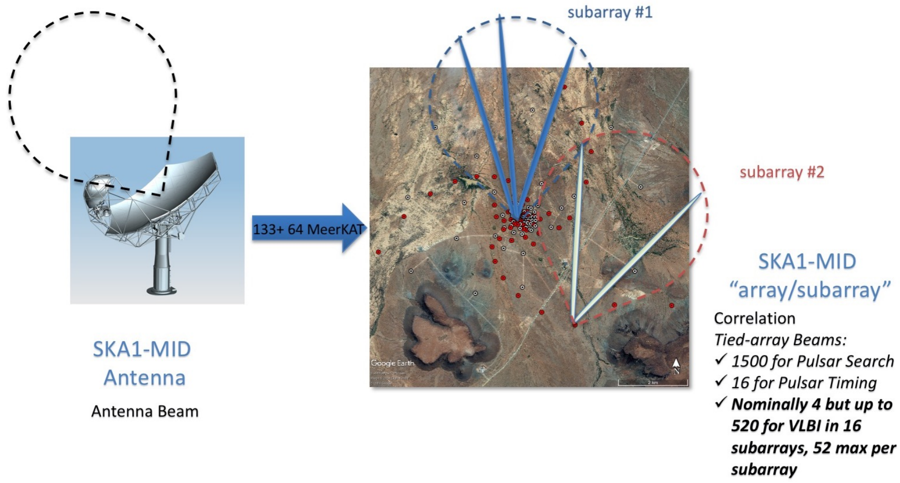

Figure 3: VLBI capability for SKA1-MID telescope. The MID correlator can process up to 16 subarrays simultaneously. The subarrays are formed by a subset of antennas, containing up to the full array (133 SKA1-MID antennas and 64 MeerKAT antennas) or just one antenna. Up to 52 VLBI tied-array beams of 200 MHz bandwidth per polarisation can be formed for each subarray independently, with a total of 520 beams formed from a maximum of 16 subarrays. For larger bandwidths, fewer beams are formed per subarray, up to a minimum of 4 VLBI beams with 2.5 GHz bandwidth per polarisation. The VLBI beams can be pointed at any direction of the sky within the primary beam of the largest antennas used in the subarray.

The VLBI beams have a maximum bandwidth of 256 MHz per polarisation. Before beamforming, at the LFAA fine channel level, RFI contamination is flagged or excised and the polarisation leakage is corrected. Each VLBI beam is channelised in up to 4 dual polarisation beam channels contiguous in frequency, with a tunable centre frequency and bandwidths ranging from 1 to 64 MHz. Digitisation uses 2 to 8 bits per sample and up to 2x Nyquist oversampling. Beam channels are formatted in VDIF packets using real representation, that are streamed to the VLBI terminal. Power levels in the beam channels and beamforming weights are provided as part of the metadata.

3.3 VLBI element of the SKA1

The VLBI element falls under the responsibility of an international VLBI Consortium. It will be composed of a VLBI terminal with VDIF recorders, monitor and control software, and the necessary scripts to carry out the observations. To allow easy access for the VLBI Consortium to the VLBI terminal, and to not impose additional burden to the very restricted RFI control at the telescopes sites, the VLBI terminal will be installed at the Science Processing Centres (SPC), located in Perth and Cape Town for SKA1-LOW and SKA1-MID, respectively.

The VLBI terminal will be comprised of a Commercial Off-The-Shelf (COTS) VLBI server, a

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

Figure 4: SKA1-MID telescope observing commensality. The MID correlator provides enough processing resources (Frequency Slice Processors, FSPs) to be able to process full Band 5 bandwidth (5 GHz instantaneous bandwidth) for one processing mode at a time: Imaging, Pulsar Search (PSS), Pulsar Timing (PST), VLBI, and Zoom windows for spectroscopy. For example for full bandwidth Imaging in Band 5, all FSPs are used, not allowing for any other simultaneous processing mode. In Bands 1 and 2, where the total instantaneous bandwidth does not exceed 1 GHz, all modes can be observed simultaneously at full bandwidth. The table shows examples of allowed commensal observations in the different bands and the resources used for each mode, i.e. number of FSPs.

COTS 100GE Ethernet Switch and one or several COTS VLBI recorders (Fig. 6). The exact number of recorders depends on the recorder performance and on the required recording data rate, with the aim of supporting 400 Gbps (MID) and 100 Gbps (LOW) maximum data rates from the SKA1 telescopes with the agreed interfaces. The data rate could easily surpass this planned capability, mainly for MID Band 5, therefore the VLBI equipment and interfaces will be upgraded during the lifetime of the SKA Observatory.

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

The VLBI VDIF recorders selected for this design are FlexBuff type recorders but other types of compatible VDIF recorders may be used in conjunction, or as an alternative (e.g. Mark 6 Haystack recorders or NAOJ OCTAVE-families). FlexBuff recorders provide a flexible and

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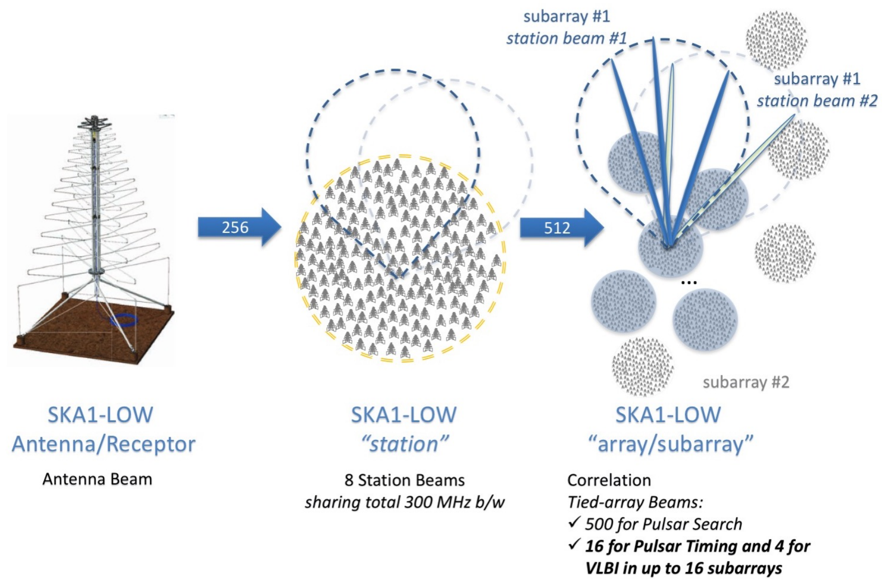

Figure 5: VLBI capability for SKA1-LOW telescope. The LOW correlator can process up to 16 subarrays simultaneously. The subarrays are formed by a subset of stations, containing up to the full array (512 stations) or just one station. Each station is made of 256 log-periodic antennas. The total instantaneous processed bandwidth is 300 MHz divided amongst up to 8 different stations beams pointed in different directions. Up to 4 VLBI tied-array beams of 256 MHz bandwidth per polarisation can be formed in total from one or up to 4 subarrays using just one station beam. If a VLBI beam needs to be pointed outside the station beam, a different station beam could be used to generate it by trading off some of the available 300 MHz bandwidth. In the event that Pulsar Timing is not being observed commensally with VLBI, up to 16 VLBI beams of 256 MHz bandwidth per polarisation could be formed from one or up to 16 subarrays.

standard COTS solution for simultaneous receive, buffer (record) and transmission of VLBI data streams. Requirements for a FlexBuff vary depending on the buffer capacity and the sustained data rate that needs to be achieved [6]. The VLBI recorders will be controlled using the jive5ab open source control software [7].

The VLBI server will implement SKA1 Local Monitoring and Control (LMC) within the Tango open source framework adopted by the SKA1 Observatory. The LMC will be responsible for Monitor and Control of the VLBI terminal and for subscription to the appropriate metadata, as well as logging events and sending alarms to the Telescope Manager. The VLBI server will implement an additional bespoke application to extract the metadata and generate the observing experiment log required by the External correlator that will be recorded in the FlexBuff recorders along with the data. The LMC will also implement a translator for jive5ab commands to control

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the recorders and use standard Tango translators for the Linux server and the Ethernet switch.

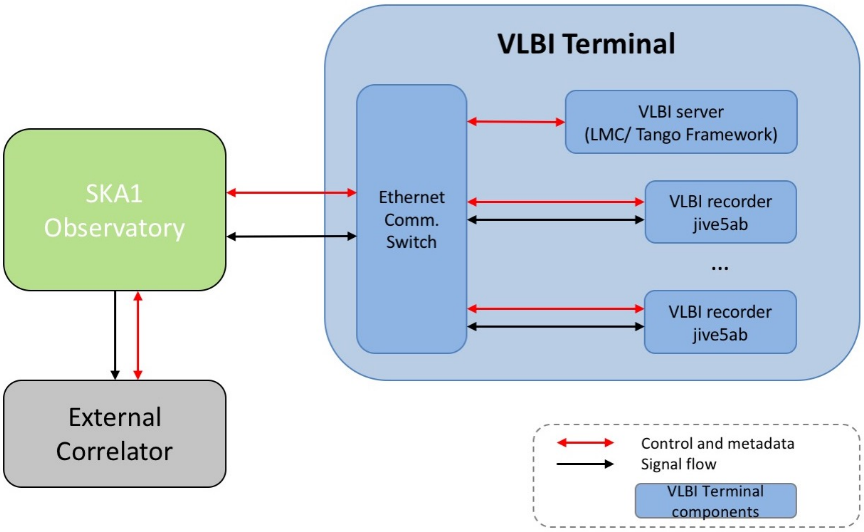

Figure 6: VLBI Terminal description.

4. SKA-VLBI Science Use Cases

The SKA1 Scientific Use Cases document [8] contains six science use cases that request the SKA-VLBI capability (out of a total of 58 cases). These were formulated before the detailed VLBI implementation was known. It is time to reconsider and update some of these use cases, as well as other, new use cases that could exploit the unique SKA-VLBI capabilities. Notably, there are no use cases for the SKA1-LOW telescope, because VLBI was not considered for this telescope in the early days of the project. This is because of the limited number of other telescopes available in the 50-350 MHz frequency range. JUMPING JIVE is engaging with the SKA Science Working Groups, Focus groups, and members of the VLBI community for the preparation of additional VLBI science cases that properly reflect the recent evolution of high-profile VLBI science with a view to exploit the full capability of the SKA1 telescopes.

The "SKA General Science meeting and Key Science Workshop" (April 8-12, 2019) and the "SKA-VLBI Key Science Projects and Operations Workshop" (October 14-17, 2019) will be ideal forums for discussions towards the inclusion of VLBI science in the future SKA Key Science Projects [2].

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