

SKA and VLBI synergies

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Abstract

VLBI is a unique tool in astronomy to study the compact radio emission of celestial bodies in extreme detail. This technique has been applied in fundamental astronomy for establishing celestial reference frames and in astrophysics to study the non-thermal continuum and maser emission of galactic and extragalactic objects. The main targets of VLBI studies are the black-hole powered active galactic nuclei and their relativistic outflows, the surfaces of stars, the atomic and molecular gas outflows, disks, and shells in star forming regions, young stars, supernovae and their products (neutron stars and stellar black holes with a companion star). Combining the SKA with VLBI arrays will provide improvement of structural sensitivity on larger scales (covered by SKA baselines alone) and help reach unparalleled flux density sensitivity on compact angular scales probed by VLBI. Here we describe some of the scientific targets of the combined SKA-VLBI and we discuss some technical issues such as the enhancement in sensitivity and the joint observations with existing VLBI elements at present.

1 Introduction

The technique of very-long-baseline interferometry (VLBI) probes compact objects in the microwave range, at angular scales from 100 millarcseconds (mas) down to fractions of mas. This corresponds to scales of several astronomical units at the distance of few kpc (e.g., microquasars in our Galaxy or the Galactic Centre), and parsec scales at distances of Mpc to Gpc (active galaxies and quasars). VLBI arrays can be combined with connected interferometers such as the VLA or eMERLIN, with the latter being the only instrument which covers properly the intermediate (mas-to-arcsecond) scale resolution. The addition of the Square Kilometre Array will provide new capabilities for the full range of resolutions between the milliarsecond and the arcsecond. It will, as well, enhance dramatically the sensitivity of VLBI arrays, if combined as a single element. In a first approach, SKA-VLBI will be possible by adding phased-array outputs for SKA1-mid to the VLBI arrays, using these sensitive stations with other radiotelescopes. In a later stage, SKA2 would add VLBI antennas to the SKA correlator, providing a VLBI instrument with baselines of thousands of km.

The high-resolution capability of the SKA has been discussed in several works (see [13] and references therein). Recent works have described in detail the options and the science of VLBI in the SKA era, such as [35, 46]. Here we will show some of the highlights, in extragalactic (Sect. 2), intermediate black holes (Sect. 2.2), and stellar astronomy (Sect. 3), respectively, and discuss some technical considerations in Sect. 4.

2 Extragalactic objects

2.1 AGN Physics & Galaxies

the study of relativistic jets in active galactic nuclei (AGN) [44] is one of the key targets for VLBI since its pioneering times. A fraction of AGN features powerful collimated outflows of plasma, which can reach distances of hundreds of kpc from the central engine. These objects have high brightness temperatures, reaching up to 10^{12} K and even higher in exceptional cases due to Doppler boosting and other effects [37]. These jets contain enhanced regions of emission which appear to move at speeds that imply high Lorentz factors, and the time evolution of these features has been studied in detail in many individual objects (e.g., [9, 10] for CTA 102, [38] for NGC 1052, [1] for OJ 287, [11] for 3C 120, or [18] for 3C 111), and extensively in imaging surveys (e.g., [45, 23]).

The inclusion of the SKA in new arrays, with its enhanced capabilities in image fidelity and detection of low brightness temperature features, will have an impact on the understanding of the jet physics, the mechanisms which govern the structure and jet kinematics. This is complementary to the present developments in the studies of the jet base at higher frequencies, especially with the inclusion of ALMA in VLBI networks in a near future [8, 39].

Magnetic fields play a major role in extracting energy from the central region and feeding the jet, which is confined by strong, collimating magnetic forces [43]. The study of the polarised emission of relativistic jets probes the nature and structure of the magnetic fields. It is often assumed that the magnetic field structure is helical from the launching in the

central black hole (e.g., [4]), but it is unclear if this helical structure persists after iteration with shocks or the external medium. The field orientation can reveal poloidal or toroidal structure, and the compression of the field by shocks perpendicularly to the jet direction can create enhanced polarised emission [21, 16]. Exhaustive studies have been performed by combining large data sets in surveys (see [22]). The polarised emission is affected by Faraday rotation when propagating through plasma, and it is being studied in detail, to see which is its effect in depolarisation, if it is caused by an external screen or if it is intrinsic, etc. Recent studies of large samples of sources reveal few cases of internal rotation, but most of the measurements are compatible with external screens ([12, 15]). The high fidelity and the increase of sensitivity provided by the SKA will help much in solving the open questions about the strength and structure of the magnetic field and its influence in the jet formation and dynamics.

The energy released by an AGN affects strongly the surrounding interstellar medium [2, 3]. The feedback regulates the growth of the central massive black hole and the star formation rate in the galaxy [26, 6]. HI spectral-line imaging of the AGN 4C+12.50 showed how the jet contributes to AGN feedback [33]. SKA-VLBI will image ultraluminous infrared galaxies (for which the infrared excess is caused by re-processed UV light from hot young stars) at unprecedented sensitivity at 18-cm wavelength. Exquisite observations of feedback with the enhanced sensitivity of the SKA-mid and combined with VLBI at 18-cm will be possible. The complex interaction between the relativistic outflows and the interstellar regions will shed light on the question of why giant elliptical galaxies have switched off star formation. The synergy of SKA-VLBI observations with future X-ray missions should provide the final answer.

Stimulated spectral line (maser) emission has been observed in extragalactic sources [24], with large luminosities, over 8 orders of magnitude larger than in galactic masers. Successful detections were performed for hydroxyl (OH) at 1.6–1.7 GHz, water (H₂O) at 22.2 MHz, formaldehyde (H₂CO) at 4.83 GHz. Recent ALMA detections of megamasers in NGC 1068 were reported for mm-transitions of methanol (CH₃OH) at 84.52 GHz and silicon monoxide (SiO) at 85.04 GHz [42]. More detections at millimetre-wavelengths are expected with ALMA, and the SKA with its sensitivity should access to further, weaker targets and potentially be able to detect other transitions such as the 23.87 GHz line in ammonia (NH₃), if this frequency is reached at some point. Redshifted megamasers will then reach the detection threshold to be observed and imaged. In this sense, the effort of the Megamaser Cosmology Project (see the white paper here and recent results at [20, 19]) with water masers could be extended to other species and with a far deeper scope.

Due to lack of sensitivity, the population of quasi-stellar objects with low radio emission has not been studied in detail. Different explanations have been proposed to address the radio-quiet nature of these objects, being a fraction of them associated to broad absorption lines (for which the wind from the accretion disk would switch off the jet), or being just thermal radiation [5]. The combination of the high sensitivity and high resolution of SKA-VLBI observations will address in a much better detail the morphology and the spectrum of the radio cores (if detected) of these objects.

2.2 Intermediate-mass black holes

Intermediate-mass black holes are the missing link between super-massive black holes and stellar-mass black holes. They should be present in the nuclei of low-mass galaxies and could be also observed in the halos of large galaxies and in the arms of spiral galaxies, where they manifest themselves as ultraluminous X-ray sources [7]. Stellar-mass black holes accreting at Eddington or super-Eddington rates could explain the X-ray emission of ultraluminous X-ray sources up to $L_X = 5 \times 10^{40} \text{ erg s}^{-1}$, but X-ray luminosities above this value need larger black hole masses (see [41, 32]). Recent results based on combined X-ray and VLBI observations show that some of these ultraluminous X-ray objects are intermediate-mass black holes accreting at sub-Eddington rates [28, 29, 30] and powering strong radio jets [31]. The highest sensitivity provided by SKA-VLBI at cm-wavelengths will allow for further detections and deeper studies in the radio regime of these ultraluminous X-ray sources.

3 Stellar physics

VLBI observations have remarkably strong impact in the Stellar physics studies. We can mention the study of Gamma Ray Bursts (GRBs), Radio Supernovae (RSNe) and Supernova Remnants (SNRs), Microquasars or Pulsars, among others. Moreover, VLBI astrometry is a unique tool providing stellar parallax measurements and proper motion determinations as well as the search for planets via the reflex motion of the star.

The addition of SKA to the Global VLBI Arrays will not increase the angular resolution of the arrays. However, it will provide an excellent sensitivity on the long baselines assuring that the scientific targets will be imaged both in total intensity and polarisation with better detail than is possible today. Additionally, the accuracy of the source sizes obtained via model fitting will also benefit from the increased sensitivity [27]. Assuming observations at 5 GHz and observations with a SNR 100-1000, the minimum source size determination will be of the order of a few tenths of milliarcsecond.

One of the immediate applications of SKA-VLBI will be the studies of explosive events in stellar objects in the Milky Way and nearby galaxies. Thanks to the sensitivity of SKA, the number of detected and monitored core-collapse supernovae will increase significantly. It will be possible to resolve any of them, studying their angular expansion for much longer periods of time, yielding information about both the circumstellar and interstellar environments and the progenitor star. For nearby galaxies, a good estimate for their star-formation rate can be obtained [36] through the detection of individual radio supernovae and supernova remnants in the circumnuclear starbursts. The extra sensitivity provided by the SKA1 phased-arrays will permit the detection of Type I-a radio supernova, giving unique insights on the nature of the progenitor systems.

A particular case of study are the Gamma Ray Bursts (GRBs). According to the collapsar model, the long duration GRBs are related to the collapse of a fast rotating star in a low metallicity environment. In the case when the star is rotating quickly enough, then the fallback to the black hole will produce relativistic jets (the GRB); on the other hand, if such a star is rotating slowly, then it will produce a faint supernova. The type Ic supernovae

are associated with GRB explosions; however, this connection has been shown only for a few cases [34]. SKA-VLBI will have the potential to study the launch of the relativistic jets and the expansion of the GRB relativistic outflows during a period of 1-2 weeks after the explosion.

Due to the superb-sensitivity provided by SKA-VLBI, the number of detected stars will be very large (hundreds to thousands). For many of them, it will be possible to measure parallaxes with precisions better than 10 microarcsec, permitting a direct comparison with *GAIA* and favouring a cross-calibration among both reference frames (the International Celestial Reference Frame (ICRF) and *GAIA*). SKA-VLBI will deliver a remarkably accurate astrometry, tracing very precisely the trajectories of stars on the plane of the sky. They will be modeled as the superposition of their trigonometric parallax and a uniform proper motion, permitting the accurate determination of distances to the parental molecular clouds [25].

For the case of stellar mass black holes, it will be possible to monitor the ejection of new plasma components following radio bursts and to determine proper motion of these components, giving insights on the launching, collimation and acceleration of the relativistic jets. Moreover, the accurate determination of the luminosities will permit to test the accretion physics in a wide range of accretion rates well below the Eddington limit.

Special mentioning should be made about studies of the proper motion of pulsars. One of the main key science drivers of SKA1 will be the study of binary pulsars in order to test gravity in the strong field case. With SKA-VLBI, it will be possible to study both pulsar proper motions and parallaxes, with an accuracy of the parallax determination becoming better than 3 microarcsec. This information will be one of the keys for exploiting the complementary pulsar timing measurements. In order to achieve the required time precision, the effects of the intervening ISM (dispersion and scintillation) should be accurately determined.

Finally, it should be mentioned that the sensitivity and accuracy of SKA-VLBI brings the possibility to detect planets directly via astrometric observations of the small periodic motions resulting from planets orbiting around active stars.

4 Technical considerations

There are two options for the potential synergy between the SKA and VLBI: i) adding VLBI dishes to the SKA as an interferometer, for which the SKA will have to correlate the external stations together with the rest of the interferometer, and ii) VLBI networks get the SKA as an additional element, either completely phased or in parts. Option i) will need optical fibre transmission of data (e-VLBI), and option ii) is in principle possible with “classical” disk-recording-plus-shipping operations, but world-wide e-VLBI capabilities should be enhanced and favoured as well.

The SKA1-low version (mostly compact) is only suitable for the option ii), and for a limited set of available antennas. Only a few VLBI antennas have receivers at 327 MHz (90 cm), namely, the VLBA, GBT, Jb-1, Ar, Wb, Nt, Ur, Sm, and the GMRT. Those are non-cooled and do not offer a high performance, which results in a limited applicability to

science.

Table 1: SEFD system noise in Jy for selected antennas

λ [cm]	90	50	30	21	18	13	6	4	2	1
SKA1-low	2.8	–	–	–	–	–	–	–	–	–
SKA1-mid	4.4	4.4	4.4	2.1	2.1	2.1	2.3	2.8	2.8	2.8
VLBA ^a	2742	2744	–	289	314	347	210	327	543	640
Y27	119	–	–	17	17	–	17	15	55	47
Gb ^b	35	28	24	10	10	12	14	15	18	22
Jb-1	132	83	–	36	65	–	80	–	–	–
Jb-2	–	–	–	350	320	–	320	–	–	910
Wb	150	–	120	30	40	60	120	120	–	–
Eb	600	600	65	20	19	300	20	20	44 ^c	90
Ar	12	–	3	3.5	3	3	5	6	–	–
Ro70	–	–	–	35	20	–	–	18	–	83
KVN	–	–	–	–	–	–	–	–	–	1288
Tm65	–	–	–	39	39	46	26	48	–	–
Hh	–	–	–	–	430	410	650	630	–	–
Pk ^d	40	40	42	30	30	110	110	43	370	81
ATCA	68	68	68	106	106	106	70	86	–	106
Tb70	–	–	23	16	16	–	–	25	–	60
Mp	340	340	340	530	530	530	350	430	1300	530
Hb	470	420	650	650	640	640	1240	560	1200	1800
Cd	900	900	800	400	400	450	550	600	750	2500
Ww	–	–	–	8000	8000	–	–	8000	–	–
Tg	–	–	–	–	–	–	–	7700	–	–

Antenna keys: VLBA–Very Long Baseline Array, Ar–Arecibo, Eb–Effelsberg, Wb–Westerbork, Jb–Jodrell Bank (1: Lovell, 76-m; 2: Mk2, 25-m), Rob70–DSN Robledo, Hh–Hartebeesthoek, Tm65–Tianma 65-m (Shanghai), KVN–Korean VLBI Network dishes (Yonsei, Ulsan, or Tamna), Tb70–DSN Tidbinbilla, Mp–Mopra, Pk–Parkes, ATCA–Australia Telescope Compact Array (5×22-m tied array), Hb–Hobart, Cd–Ceduna, Ww–Warksworth, Tg–Tigo (earlier in Chile, planned to move to Argentina). ^a: VLBA Observational Status Summary 2015B.; ^b: GBT performance at NRAO web; ^c: Effelsberg Wiki Page ^d: For the LBA antennas, see their nominal SEFD values

The SKA-mid will include dishes observing at frequencies of 350 MHz to desirably 14 GHz. The antennas will be arranged with a central core of up to 3 km with arms extending to a radius of 100 km from the centre. This makes both options i) and ii) feasible. The frequency setup is compatible with the standard VLBI wavelengths of 49, 30, 21, 18, 13, 6, and 5 cm (2 cm in the future). The typical system equivalent flux density¹ will be of 1.7 Jy.

¹SEFD, defined as the flux density of a radio source that doubles the system temperature. The baseline sensitivity for two antennas with SEFD₁ and SEFD₂ is $\Delta S = \sqrt{\text{SEFD}_1 \times \text{SEFD}_2} / [\eta_s \cdot \sqrt{2} \cdot \Delta\nu \cdot \tau_{\text{ff}}]$ Jy, where $\eta_s \leq 1$ accounts for the VLBI system inefficiency, $\Delta\nu$ is the bandwidth in Hz, and τ_{ff} is the fringe-fit interval

Eventually, the core of the SKA in the Phase 2 would reach values of 0.27 Jy. In Table 1 we show the sensitivity for selected antennas to be part of such an array. Following the EVN status table, most antennas have receivers at 18/21 cm, and at 6 cm.

Option i) will only be feasible in the full SKA2 realisation, at a later point, with antennas connected by optical fibre (e-VLBI), and with an enhanced correlator.

Option ii) with SKA1-mid will have a VLBI network with a much enhanced image sensitivity at long baselines. SKA-mid will participate as a very sensitive element in conventional VLBI arrays. SKA-mid beats in sensitivity of most telescopes, and is comparable to Arecibo (although this antenna is only available for a limited region of the sky in a short period of time due to the elevation constraints). In Table 2 we show the common range of time for different elevations for a realisation of the SKA in South Africa and Western Australia.

When SKA-mid is phased to participate as the most sensitive dish of the SKA-VLBI array, the beams of the tied-array are narrower than the field of view of the individual telescopes that form the VLBI array. They can be even smaller than the typical separation between the target and the phase calibrator source. Thus, an additional SKA-phased array beam will be required per phase calibrator. Additionally, it has been shown that the use of multi-view approaches (observations of a number of phase calibrators (≥ 3) to map the spatial atmospheric distortions around a certain VLBI target) improves the phase determination, image quality and astrometric accuracy [17]. In this case, some additional tied array beams (as many as phase calibrator sources) will be needed.

The option ii) for VLBI operations will be of extreme interest when combined with future space VLBI missions, for which new frontiers in sensitivity (with a ground array enhanced with the SKA) and resolution will be reached.

It should also be mentioned that the total intensity and polarisation calibration (both leakage terms and the determination of the absolute orientation of the electric vector) of the VLBI data will benefit from the availability of both the phased-array (for the SKA-VLBI array) and the local SKA interferometric data.

5 Concluding Remarks

SKA-VLBI will improve the sensitivity of the current VLBI arrays, providing unique contributions in different research fields like the study of transients or the accurate determination of distances and luminosities. It will probe the central engines of stellar, intermediate mass and massive black holes with unprecedented sensitivity. HI observations will permit to test the feedback mechanisms between the central AGN and the host galaxy. Thanks to its superb astrometric capabilities, SKA/VLBI will determine accurately pulsar and stellar parallaxes, providing for the case of pulsars in binary systems the most stringent tests of gravity. The amplitude and polarisation calibration of SKA-VLBI will be very accurate thanks to the combination of the SKA1 and the SKA-VLBI interferometric data. The developments in the

in seconds (less than or about equal to the coherence time) [40]. The theoretical image sensitivity for an homogeneous array with natural weighting would be $\Delta I_m = \text{SEFD}/\eta_c \sqrt{N(N-1)t_{\text{int}}\Delta\nu} \text{ Jy beam}^{-1}$, where N is the number of stations and t_{int} is the total integration time on source in seconds.

SKA will complement present and future efforts in e-VLBI, and in space VLBI. In order to be competitive in terms of angular resolution and optimize the scientific return, the high frequencies (Band 5) are needed and should be promoted within the project.

Table 2: Common visible time in hours for the SKA sites with other array elements

South African SKA									
Dec	W. Aus.	JP	CN	NZ	CL	USA-HI	USA-NM	USA-PR	Europe
+45°	0.0	2.2	5.4	0.0	0.0	0.0	1.5	3.6	5.4
+30°	0.0	2.7	7.6	0.0	0.4	0.0	1.8	4.4	8.0
+15°	0.0	2.7	7.3	0.0	2.3	0.0	1.8	4.8	9.4
0°	0.8	2.5	6.8	0.6	3.7	0.0	1.7	5.0	9.1
-15°	2.0	2.1	6.3	1.9	4.9	0.0	1.4	5.1	7.8
-30°	3.0	1.2	5.4	3.1	6.2	0.0	0.0	5.2	3.0
-45°	4.0	0.0	0.0	5.2	7.9	0.0	0.0	5.2	0.0
-60°	5.5	0.0	0.0	11.8	11.6	0.0	0.0	0.0	0.0
-75°	12.9	0.0	0.0	24.0	24.0	0.0	0.0	0.0	0.0
-90°	24.0	0.0	0.0	24.0	24.0	0.0	0.0	0.0	0.0
Western Australian SKA									
Dec	ZA	JP	CN	NZ	CL	USA-HI	USA-NM	USA-PR	Europe
+45°	0.0	5.3	5.3	0.0	0.0	4.0	1.3	0.0	5.3
+30°	2.0	7.9	7.9	3.2	0.0	4.8	1.7	0.0	4.5
+15°	3.5	8.6	9.2	5.2	0.0	5.1	1.7	0.0	3.8
0°	4.5	8.5	6.7	6.6	0.0	5.3	1.6	0.0	3.2
-15°	5.5	7.8	8.3	7.8	0.4	5.4	1.3	0.0	2.3
-30°	9.0	5.1	6.2	9.1	1.9	5.5	0.8	0.0	0.4
-45°	7.7	0.0	0.0	10.8	5.2	5.4	0.0	0.0	0.0
-60°	11.5	0.0	0.0	14.1	11.7	5.1	0.0	0.0	0.0
-75°	24.0	0.0	0.0	24.0	24.0	0.0	0.0	0.0	0.0
-90°	24.0	0.0	0.0	24.0	24.0	0.0	0.0	0.0	0.0

Key: W. Aus.: Western Australia; ZA: South Africa; JP: Japan, CN: Eastern China; NZ: New Zealand; CL: Chile (latitude of former TIGO site); USA-HI: Hawaii; USA-NM: New Mexico; USA-PR: Puerto Rico; Europe: Id.

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