SKA in VLBI: Impact on Studies of Small Scale Structures in Active Galactic Nuclei

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We discuss the advantages of an electronically steerable interferometer of a million square meters collecting area operating at cm-wavelengths as a phased array and in conjunction with other antennas in VLBI mode. With a sensitivity to $\mu$Jy-level flux densities, a brightness temperature limit of $T_B = 10^4$ K, and an expected dynamic range in future VLBI images of better than $10^6$, the impact of SKA on the research on compact galactic and extragalactic radio sources will be virtually unpredictable, but certainly strong. In conjunction with future space VLBI missions and complementary to planned large interferometers operating at millimeter wavelengths, SKA bears the potential to revolutionize astronomy and our picture of the Universe. In this article we briefly outline the improvements expected from the use of SKA for VLBI in general. Then more specifically, we discuss the anticipated progress for the research on active galactic nuclei (AGN) and their powerful jets, emanating from hypothetical supermassive black holes. We will point out that beside a wealth of new details which SKA should reveal on jets, accretion disks and black holes, it will help to understand the relationship between the various types of active galactic nuclei (quasars & galaxies) and their cosmological evolution.

1 Introduction

Since the late 1960s, the observational technique of Very Long Baseline Interferometry (VLBI) has evolved enormously, yielding results from first detections of ultracompact structures and superluminal motion in AGN in the early years to present day high fidelity monitoring of extragalactic radio jets, showing details at multiple frequencies of structure and kinematics from sub-milliarcsecond to sub-arcsecond scales. Although the use of more homogeneous VLBI arrays (e.g. with the VLBA of the NRAO, 10 identical 25 m antennas) and the combination of up to 20 antennas in so called ‘world array’ experiments have considerably improved the quality of the images achieved, VLBI to date still is limited in sensitivity (to mJy level) and also by a somewhat uneven coverage of the uv-plane, which adversely affects the image reconstruction.

The somewhat stochastic distribution of radio telescopes around the world (most of them with diameters in the 10-30 m range located on the northern hemisphere) causes problems with signal detection on less-sensitive baselines, gaps in the uv-plane, and problems with image deconvolution and sidelobes. So far, only a few of the VLBI maps presented in the literature reach the thermal noise limit and have a dynamic range (defined as ratio of peak flux to noise level) better than $10^4$. The sensitivity to partially resolved sources or source components of low surface brightness is at present limited to a typical brightness temperature of $T_B \geq 10^6\ldots7$ K.

With system temperatures of only a few tens of Kelvin at cm-wavelengths, and observing bandwidths already reaching the GHz range in the foreseeable future (256 MHz to date), a further improvement of VLBI imaging capabilities can only be achieved by an increase of the total collecting area and an improvement of the uv-coverage, i.e. increasing the collecting area and number of the participating antennas.

In this contribution we shall discuss the substantial improvements to science, and in particular to the research on compact extragalactic radio sources, if the planned Square Kilometer Array (SKA) is used in its configuration with long baselines ($500 - 1000$ km maximum antenna spacing). As stand-alone instrument its resolution will be limited to a few ten milliarcseconds, so we assume here that SKA is added as a phased array into existing or future global VLBI networks operating from ground and space.
2 Sensitivity

For a Very Long Baseline Interferometer the 1σ detection threshold $\sigma_{ij}$ (in [Jy]) for detecting the fringe visibility on a single baseline is:

$$\sigma_{ij} = \frac{1}{\eta_i \eta_j} \cdot \sqrt{\frac{T_{\text{sys}}^i}{g_i}} \cdot \sqrt{\frac{T_{\text{sys}}^j}{g_j}} \cdot \frac{1}{\sqrt{\Delta \nu \cdot \tau}}$$

(1)

where $T_{\text{sys}}$ in [K] is the system temperature of the i-th antenna, $g_i = 2.845 \cdot 10^{-4} \cdot \eta_i \cdot D_m^2$ is the gain in [K/Jy], $\eta_i$ is the aperture efficiency, $D_m$ is the antenna diameter in [m], $\eta_c$ is the quantization loss factor, $\Delta \nu$ is the observing bandwidth in [Hz] and $\tau$ is the integration time in [sec].

From the above equation the sensitivity of a VLBI image ($\Delta S$ in [$\mu$Jy/beam]) can be estimated using:

$$\frac{1}{\Delta S^2} = \frac{\tau}{T} \cdot \sum_{i,j} \frac{1}{\sigma_{ij}}$$

(2)

For the calculations we assume that in addition to the existing VLBA (10 x 25 m antennas), a world array consisting of about $N \approx 20$ telescopes (e.g. the VLBA, the phased VLA, the phased MERLIN interferometer and some European antennas) also participates in VLBI observations. We further assume that observations are made at a frequency of 5 GHz with an observing bandwidth of $\Delta \nu = 128$ MHz at present, and of $\Delta \nu = 512$ MHz in the future (SKA, ARISE), using 1-bit data sampling ($\eta_c = 0.64$), a segmentation time equal to a coherence time of $\tau = 300$ sec at 5 GHz and a total integration time on source of $T = 12$ h.

Following the specification of SKA outlined in Taylor and Brown (1999), [1], we assume a system temperature $T_{\text{sys}} = 50$ K, and a total collecting area of $A = A_{\text{eff}} / \eta_A = 2.3 \cdot 10^6$ m² ($\eta_A = 0.5$). This corresponds to $N = 32$ antennas each of $D = 300$ m diameter. We also assume that SKA can be operated either in single antenna mode (some or all antennas equipped with VLBI recording equipment) or as a phased array, the latter acting as a single big antenna in a VLBI world array. Since SKA will be a transit instrument (flat array), the direction-dependent gain (or the aperture efficiency) will be maximum near zenith. It is desirable that the variations of the gain as a function of hour angle (or elevation) should not be too strong, e.g. $\Delta g / g \leq 0.5$ for hour angles of ±6 hrs. For simplicity we neglect any variation of the gain in our calculations.

For comparison of the sensitivity between present VLBI observations and future observations including SKA, we summarize baseline and image sensitivities in Table 1. With regard to VLBI observations in combination with orbiting antennas (space-VLBI), we included the 8 m antenna of the Japanese space mission (VSOP). For a future space-VLBI mission we used ARISE ($D = 25$ m) as a representative project (e.g. Ulvestad and Linfield, 1998, [2]).

Table 1 shows that the addition of a phased SKA to an existing global VLBI network will lower the single-baseline detection threshold by a factor of at least 15, facilitating instantaneous fringe visibility detection of compact sources of $\geq 10 \mu$Jy flux density. This leads to an improvement of the image sensitivity by a factor of at least 50. For a typical compact source with a flux density of 1 Jy the dynamic range in future VLBI images might then exceed $10^6$, 1–2 orders of magnitude larger than presently achieved. If SKA were operated as a phased array together with other antennas of the 100 m class in a future ‘world array’ (e.g. together with the 100 m telescopes at Bonn and at Green Bank, the 300 m antenna at Arecibo and the Chinese FAST telescope (cf. Peng Bo et al., this conference), baseline and image sensitivities of 1 $\mu$Jy and 0.1 $\mu$Jy/beam could be reached. Since the maximum separation between the individual antennas of the SKA probably will be limited to $\leq 1000$ km, the addition of other antennas at larger distances is desirable to achieve the highest possible angular resolution.

The sensitivity of a two-element interferometer is proportional to the geometric mean of the collecting areas of the two elements. The combination of a bigger with a smaller antenna therefore is equivalent to the use of two medium-size identical antennas. In a global VLBI array consisting mainly of small- and medium-size antennas, the addition of one large antenna improves the imaging capabilities of the whole
### Array baseline sensitivity image sensitivity comment

| Array              | baseline sensitivity | image sensitivity | comment          |
|--------------------|----------------------|-------------------|------------------|
| VLBA               | 2.                   | 30.               | standard today   |
| World Array        | 0.3                  | 5.                | best today       |
| SKA + VLBA         | 0.018                | 0.4               | improvement/standard 75 |
| SKA(1)-SKA(1)      | 0.011                | 0.04              | improvement/standard 750 |

Table 1: Baseline and image sensitivity for present and future VLBI observations. SKA denotes the phased square kilometer array (32 antennas), SKA(1) denotes a single element ($D = 300$ m) of SKA.

array proportionally to the number of baselines to the large antenna. This facilitates fringe detection on weaker sources and, via the construction of closure triangles, fringe detection also on the less-sensitive baselines (global fringe fitting).

It has been pointed out previously that the combination of a small orbiting antenna in space with a large antenna on the ground is financially much more attractive than launching a big antenna into space. In future space VLBI missions (e.g. ARISE), SKA can therefore play a very important role. Its impact on space VLBI probably could be even greater than for ground VLBI. In the lower part of Table 1 we compare the gain of baseline sensitivity in a present space VLBI experiment with, for example the 100 m antenna at Bonn and VSOP, and with SKA and ARISE in the future. The improvement will be two orders of magnitude!

### 3 Angular Resolution and uv-Coverage

The geometrical configuration of the antennas of SKA is still being discussed. For VLBI, a configuration as proposed by Taylor & Brown is useful. In Figure 1 we show a simulated uv-coverage for an experiment involving the European VLBI Network (EVN) and the MERLIN interferometer. For the simulation we replaced MERLIN by the SKA interferometer. For the configuration of SKA a Y-shaped geometry (nine antennas arranged on the three 500 km arms) and a central area covered by two elliptical rings (diameter $\leq 50$ km) of concentrically arranged antennas (cf. Taylor & Braun 1999). The 500 km arm length gives an angular resolution of 18 mas. For a source of $S = 1 \mu$Jy, the minimum detectable brightness temperature at 5 GHz will then be $T_B = 150$ K. The addition of the EVN to SKA will improve the angular resolution to 4–5 mas. To reach higher angular resolution, longer baselines have to be included (unless the antenna spacing of SKA is increased to world-wide separations). For VLBI observations with transcontinental baselines, an angular resolution of 1 mas can be achieved in ground-based VLBI observations at 5 GHz. With baselines to an orbiting antenna at 40 000 km altitude (ARISE) 0.3 mas will become possible. For a source at a redshift of $z = 0.1(1)$, this corresponds to a spatial resolution of 0.4 (1.3) pc (for $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$). The minimum detectable brightness temperature in this larger configuration then will be $T_B = 10^4$K (ground) and $10^5$K (space), which is two orders of magnitude lower than presently achieved.

The combination of SKA with existing or future telescope in a global VLBI array offers, besides the sensitivity improvement, some other advantages:

(i) To achieve the highest angular resolution for ground based observations, the spacing between individual antennas of SKA need not be extended over more than a few hundred kilometers. This limits the costs for data links between the antennas (e.g. fiber optics) and facilitates operation as one phased array.

(ii) present day VLBI observations usually lack short baselines, rather than long baselines. To satisfy
Figure 1: Simulation of the uv-coverage for a hypothetical circumpolar source observed 12 hours with VLBI. The uv-coverage is shown on the left. On the right the visibility amplitude is plotted versus projected baseline length. For the source a core dominated core-jet structure of 5 mas length was assumed. On top a VLBI experiment was simulated assuming mutual observations of the European VLBI Network (EVN) and the MERLIN interferometer. In the simulation below, the MERLIN interferometer was replaced by the SKA interferometer. For the SKA a geometry as described in the text with an arm lengths of 500 km was chosen. Note that SKA nearly fills the uv-plane for $<15 \lambda$.

For the interests of non-VLBI observers, SKA has to provide mainly short uv-spacings (emphasis to 10-100 km baselines). In our simulation (see Figure 1), SKA contributes mainly at uv-spacings $\leq 15 \lambda$. In this area it nearly fills the uv-plane. Therefore, one of the main advantages SKA could offer for VLBI is the potential to close the gap between long and short uv-spacings. This will allow us, better than presently possible, to image source structures continuously from milliarcsecond to arcsecond scales (compare with the wide-field imaging technique addressed by M. Garret, this conference). Future high-fidelity images resulting from a combined SKA+VLBI interferometer will allow one to ‘zoom’ continuously from outer- to inner-scale structures within the same data set. This is important for example for the investigation of jets in active galaxies (radio galaxies, Seyfert galaxies, etc.) or for the imaging of gravitational lenses.

(iii) in aperture synthesis, the image quality depends on the number of participating telescopes. The combination of SKA with other VLBI telescopes would introduce a large number of baseline combinations ($N(N-1)/2$, $N \geq 30 - 40$), depending on how many of the individual SKA antennas will be equipped with VLBI recording equipment. This would provide a uv-coverage with high...
redundancy, much more dense than presently synthesized. Facilitated by the usage of closure relations (for phases and amplitudes) a much better self-calibration of the data and an improved fidelity of the final images (dynamic range: $10^6$...) will be achieved.

4 General Improvements

In summary, a next-generation interferometer like SKA will provide for VLBI, high sensitivity ($\mu$Jy-level), quasi-continuous uv-coverage (from arcseconds to milliarcseconds), a brightness temperature limit of $T_B \geq 10^4$ K, and a map fidelity of better than $10^6 : 1$ (dynamic range). As a phased array, SKA will provide an angular resolution of 20-30 mas. With other VLBI antennas added to it, 1 mas can be reached from ground, and about $\sim 0.3$ mas using an orbiting antenna.

With this, first of all, more and fainter compact radio sources can be observed. The study of more distant quasars (QSO) and radio galaxies (RG) will allow us to understand better their evolution (luminosity functions) and will allow sophisticated tests on cosmology ($H_0, q_0$, inflation). Detecting and imaging the large number of radio quiet QSOs and faint radio counter-parts of galaxies that are bright at other wavelengths will have its impact on unification models of AGN. The study of cores of galaxies and Sgr A*-like objects in other galaxies (e.g. M 81, NGC 4258) will eventually lead to detections of supermassive black holes, accretion disks and general-relativistic effects in their vicinity. In gravitational lenses, the multiple images can be studied with quasi-continuous resolution from milliarcseconds to tens of arcseconds, allowing studies of the cosmological metric (time delay along path) and cosmological propagation effects. There is hope that even the (dark) lensing galaxies will become directly observable. With brightness temperatures $> 10^4$ K, compact extragalactic H II regions, regions of starbursts and supernova remnants would become observable. Systematic studies of supernova expansions in external galaxies can be used to improve the distance ladder. With a sensitivity $> 1000$ times better than to day, the radio-interferometric investigation of various kinds of radio stars, peculiar binaries, pulsars, etc. will be pushed forward, revealing insight in other radiation processes than just thermal or synchrotron radiation. Radio interferometric observations provide the highest positional accuracy in astrometry (accuracy range: $10^{-3} \ldots 10^{-6}$ arcsec). The detection of planets around $\mu$Jy-bright (radio) stars and the monitoring of stellar motion should then become feasible for many objects, using phase referencing techniques.

5 Study of Jets in AGN

The activity in active galactic nuclei (AGN: QSOs, BL Lacs, Blazars, OVVs, HPQs, ...) manifests itself primarily in intensity variations (total intensity and polarization) with time scales ranging from minutes to years. Often, the variations are correlated over wide bands of the electromagnetic spectrum ($\gamma$-rays to radio wavelengths) and appear first and with shorter duration at high frequencies and subsequently propagate towards longer wavelengths and longer timescales. In many sources observed with VLBI, correlations between the intensity variations and the ejection of sub- or superluminal components from the VLBI core are observed. In the context of such rapid variability, SKA can contribute significantly to the investigation of the quasar phenomenon. It could help to answer the important questions of how energy is converted near black holes, how the highly relativistic jets are made and how they propagate. This contribution of SKA is complementary to the expected contribution of other large instruments planned e.g. at millimeter wavelengths.

Due to its high observing frequency and angular resolution, VLBI at millimeter wavelengths (mm-VLBI) can detect new ejected jet plasma (= new components) earliest after the initial flaring. These features appear at core separations as low as a few ten micro-arcseconds ($40 \ldots 50 \mu$as are presently achieved at 86 GHz). In future, the activity in AGN and their outburst-ejection relations need to be studied in more detail. The future mm-VLBI networks will include large phased interferometers (e.g. BIMA, IRAM, OVRO, NRO). The addition of the planned Atacama Large Millimeter-Array (ALMA, the former LSA/MMA) to mm-VLBI will yield very high sensitivity ($\mu$Jy-level). The role ALMA will play for astronomy at mm-wavelengths (cf. Krichbaum, 1996, [3]), SKA will play at...
cm-wavelengths.

At the longer mm- and at short cm-wavelengths space-VLBI observations including SKA will provide high angular resolution, which will allow us to follow the injected jet components at or slightly below the self-absorption frequency, in the transition region between optically-thick and optically-thin radiation of the jet. Ground based VLBI observations with SKA at the longer cm-wavelengths will provide highest sensitivity and will reveal finer details in jets on all angular scales > 1 mas. The profiles of jets in total intensity and polarization, their widths and ridgeline, their curvatures and spectral shapes could be imaged continuously from the base (or nozzle) out to the hot spots. For the latter, their advance speeds could be measured. With a dynamic range of order $10^6$, the motion of the more central features in the jet (let it be pattern or bulk motion, motion of shocks or propagation of instabilities) can be followed over much longer distances and times than presently possible. Loosing a moving and slowly synchrotron-decaying component as it falls below sensitivity limit would no longer happen on mas-scales but on scales of tens to hundreds of mas. Spectral-index studies will become possible over a larger distance along the jet.

Features in jets usually do not move ballistically. They accelerate or decelerate, change direction of motion and quite often seem to move along quasi-sinusoidal bent paths, suggesting motion along spatially bent and helical trajectories. Before discussing jet intrinsic properties, the geometric effects on the observed variability pattern (e.g. flux, speed) have to be eliminated. At present, however, it is unclear whether this helical motion is caused externally, in a flow along a helical magnetic field e.g. anchored in a rotating accretion disk, or if it is due to jet intrinsic processes, like Kelvin-Helmholtz or magneto-hydrodynamical instabilities. With total intensity and polarization maps of sufficiently high dynamic range it should be possible to discriminate between intrinsically three-dimensional motion, which would cause systematic and correlated variations of velocity, brightness and polarization, and alternative kinematical scenarios, e.g. collectively moving patterns, kinks or wiggles, which would be more typical for instabilities. From high-quality maps the modes of such instabilities (the wavelength and amplitude of the oscillation of jet axis and width) could be determined much more accurately than at present. This will improve our knowledge of still largely unknown physical parameters of jets, like intrinsic velocity distribution, magnetization, pressure and density contrast (light or heavy jets?).

Another important topic is the physics of shocks and how the acceleration of particles (electrons, positrons, protons) in jets occurs. The relative abundance of these particles in the jets and their energy distribution is also largely unknown. Obviously, the radiating relativistic particles of the jet have to be reaccelerated, but at present it is unclear if this is done only by shocks. It is commonly assumed that the components detected with VLBI in jets are related to relativistic shocks, which can be moving or stationary, thin or thick, oblique or transverse, and being polarized parallel or perpendicular to the jet axis. The observed flux density variations can be explained by shock-in-jet scenarios, at least to some extent. High dynamic range imaging of jets in total intensity – and perhaps more important – in polarized light, will allow us to study how the shocks evolve in time and frequency, if they fill the jet widths or only part of it (filling factor, obliqueness), if and how they are magnetized (linear or circular polarization), how the observed motions couples to the underlying flow (is $\beta_{\text{jet}} = \beta_{\text{shock}}$?), and if there is evidence for magnetic reconnection or other collective emission processes. With higher angular resolution (space-VLBI), the detailed structure of shocks, their internal stratification, reverse shocks, back-flows and rarefaction regions could be investigated and theory could be tested.

The observed brightness $S$ of a relativistic flow (jet), which is inclined towards the observer depends on the Doppler-boosting factor $D$, which itself is a function of Lorentz factor $\gamma = (1 - \beta^2)^{-0.5}$ and jet inclination $\theta$: $S \propto D^{2+\alpha}; D = \gamma^{-1}(1 - \beta \cos \theta)^{-1}$, where $\alpha$ is the spectral index ($S_{\nu} \propto \nu^{\alpha}$) and $\beta = v/c$ is the jet speed. The relativistic effects determine the intensity ratio between jet, pointing towards the observer, and counter-jet, pointing away from him. The extremely high dynamic range ($10^{6-7}$) of future images made with SKA and VLBI will allow us to measure accurately the jet-to-counterjet ratio even for the so called one-sided sources (QSOs, BL Lacs, ...), which are thought to be oriented at small ($\leq 10 - 20^\circ$) inclination angles and in which the brightness of the counter-jet is strongly attenuated. For sources that are oriented at larger inclinations (two-sided radio galaxies, Seyfert galaxies, etc.) the high sensitivity of such images to low-surface-brightness features will make it possible to overcome the selection bias towards specific jet velocities in inclined radio jets (see Figure...
Figure 2: Flux density plotted versus inclination angle to the line of sight for a fast (Lorentz factor $\gamma = 20$) and a slow ($\gamma = 1.1$) relativistic flow. At small angles, the emission from the high-$\gamma$ flow dominates, while at large angles the low-$\gamma$ flow is brighter. For inclined jets, this introduces a selection bias; the observer will see the part of the jet with the appropriate Lorentz factor. To study the internal velocity distribution in jets of quasars and radio galaxies, high dynamic range images like those expected from SKA will be needed.

This might lead to the detection of high-velocity flows in sources oriented at large angles, or low-velocity flows in sources oriented at small angles. Such multiple flows are not unexpected and their existence may solve some problems of present-day models regarding source unification. From a known jet-to-counter-jet ratio and from the velocities, the intrinsic geometry and the distance of the sources can be determined. The study of two-sided jets (cf. A. Roy et al., this conference) is ideally suited to test the unification models, which try to explain differences between various source classes as due to geometrical effects in an inclined system of accretion disk (thin or thick) and two sided jet emission (radio galaxies $\leftrightarrow$ blazars, Seyfert 1 $\leftrightarrow$ Seyfert 2 galaxies, FR I galaxies $\leftrightarrow$ BL Lacs, etc.). In such a geometry the separation between the footpoints of jet and counter-jet depends on observing frequency and on the brightness of the counter-jet, which is reduced by absorption from the accretion disc located in front of it (free-free absorption). High angular resolution studies with VLBI and SKA in spectroscopic and continuum mode at different frequencies will allow us to determine the geometrical and physical parameters of accreting supermassive black hole systems and their jets. This will help us to unravel the relation of the various classes of AGN (quasars, galaxies) to each other, improving our knowledge of the cosmological evolution of galaxies and quasars.

6 Summary

Ground-based observations are logistically easier to perform, can be used by a larger scientific community for a longer period of time, and usually are cheaper than pure satellite-based experiments. One of the two windows that the atmosphere offers to observers is the radio window. SKA offers micro-Jansky sensitivity for research in this band. With this sensitivity an unpredictable number of discoveries can be made, even though the radio band has been exploited for more than 50 years. With a collecting area of order of a million square meters, SKA can provide a break-through to imaging in radio astronomy and to our knowledge about the Universe. The construction of SKA will be technically and financially challenging, but worth the effort.
In this paper, we discussed the addition of SKA as a phased array to existing or future VLBI networks. This will allow studies of virtually all types of compact galactic and extragalactic radio sources with unrivaled image quality and angular resolution. For the first time it will be possible to ‘zoom’ into extended radio sources with continuous uv-coverage ranging from arcseconds to milliarcseconds. In conjunction with orbiting antennas, an instrument like SKA will be required to provide the sensitivity needed for studies of the most distant (and therefore faint) radio sources with sub-milliarcsecond resolution. For closer sources, the high spatial resolution which VLBI with SKA offers will facilitate finer images and more detailed studies of the central regions of AGN and their jets. In future interferometers operating at millimeter wavelengths (e.g. ALMA, mJy-sensitivity) and centimeter wavelengths (e.g. SKA, µJy-sensitivity) will complement each other perfectly. The complementary scientific return of both instruments will allow to answer many of the unsolved problems and questions, in particular those related to the quasar phenomenon, to the cosmological evolution of galaxies and to the chemistry of matter in space.

References

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