SKA Astrometry

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Abstract

We report on the astrometric capabilities of the different configurations of the SKA. For SKA1-MID, the large enhancement in sensitivity will allow astrometric studies at sub-mas level of a wide variety of objects well below the detection threshold of present VLB arrays. Microarcsecond astrometric accuracy will necessarily come from combination of SKA1-MID with existing VLBI networks or from the SKA2 realization using conventional in-beam phase-referencing or Multiview techniques. We describe some astrometry projects that will become accessible with the SKA.

1 Introduction

The measurement of the motion and size of the celestial bodies constitutes the foundations of our present understanding of the universe. The progressive improvement of the astrometric accuracy has permitted to attack and solve new questions in astrophysics. During the past decades, radio interferometric techniques have provided a giant improvement of the precision of astrometric accuracy, going from arcseconds to the microarcsecond level at cm-wavelengths.

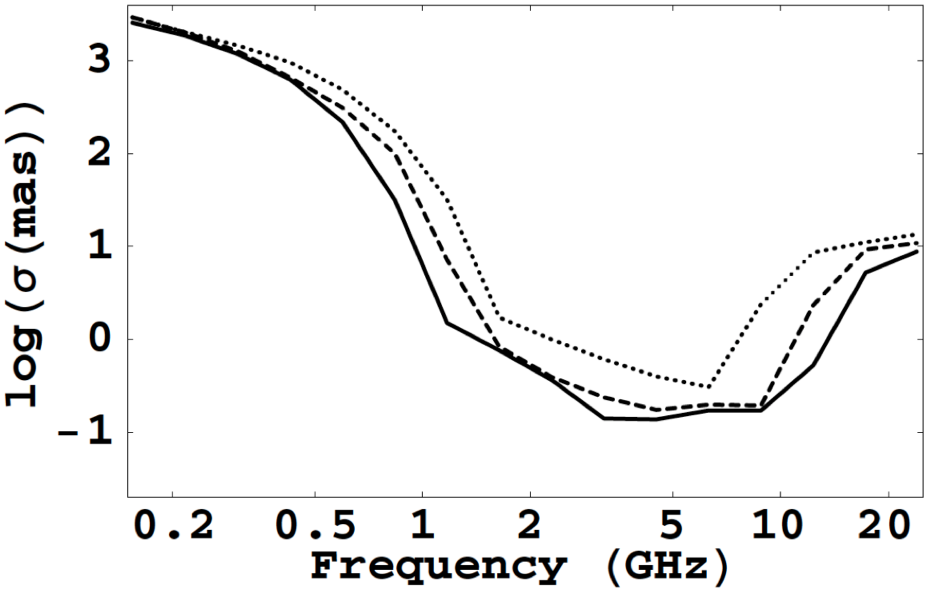

Figure 1: Astrometric accuracy as a function of frequency of an interferometric array with maximum baselines of 3000 km (after the simulations reported in [13]). Typical atmospheric turbulences and a target-calibrator separation of 5 deg are considered. Different flux densities of the target source are plotted, 10 μJy (continuous line), 1 μJy (dashed line), and 0.1 μJy (dotted line).

Accordingly, a number of astronomical events have been either discovered or tested via radio astrometry [18] covering a wide range of fields from star formation until cosmology including tests of general relativity. The advent of the SKA will boost the sensitivity to the order of tens of nJy, and combined with dedicated calibration techniques will allow the access of radio astrometry to new astrophysical scenarios. The astrometric capabilities of SKA have been discussed in previous works [7, 17]. Here we explore the limits of the astrometric accuracy of SKA both working as a standalone array and in combination with existing radio telescopes.

2 Astrometry with SKA

In absence of atmosphere, the theoretical astrometric uncertainty of an interferometric array, σ_{th}, can be expressed as [21]:

$$\sigma_{th} \sim \left(\frac{\theta_0}{\mathrm{D}}\right) \tag{1}$$

where θ_0 is the size of the beam, and D is the dynamic range of the image of the target source. Using present VLBI arrays at cm–wavelengths, typical values of σ_{th} may reach

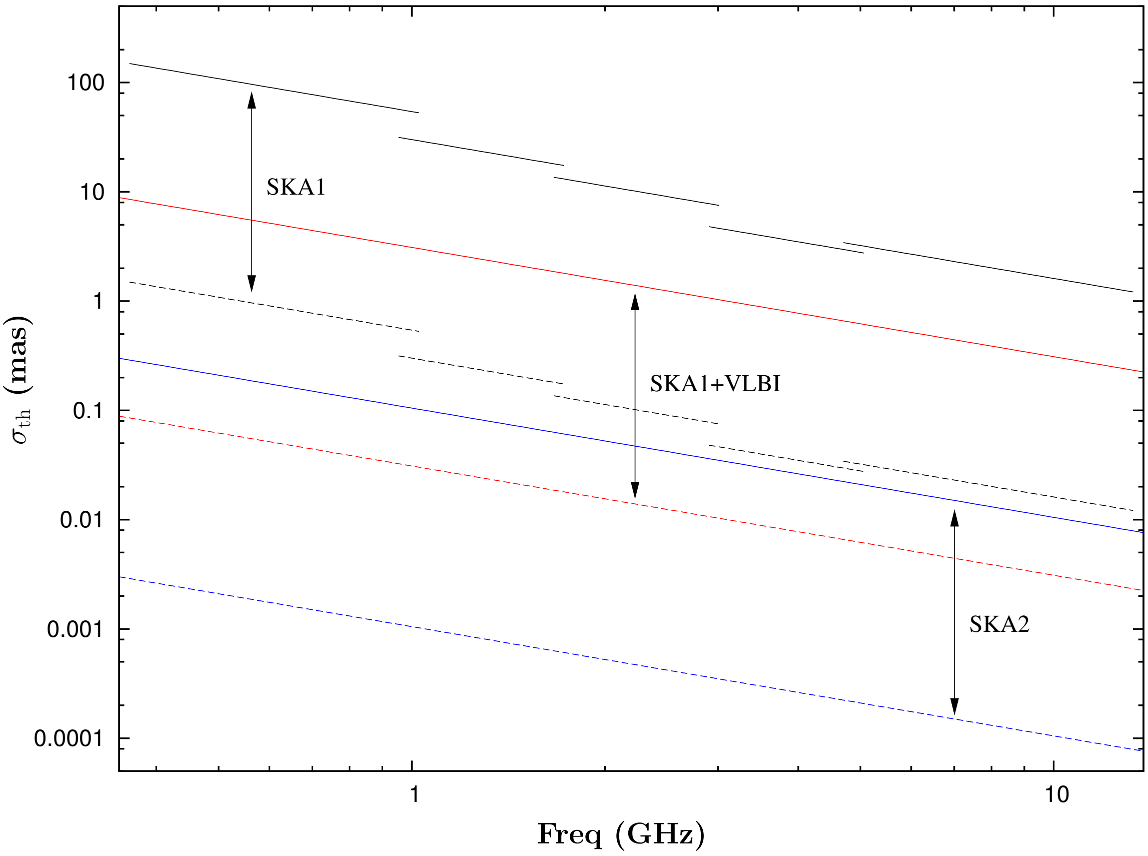

Figure 2: Theoretical astrometric accuracy of different SKA configurations (see text). For each configuration, two flux densities of the target source are considered, 10 μJy (continuous lines) and 1 mJy (dashed line). Dynamic range values have been calculated using the sensitivities given in [20] for 1 hr integration time.

the microarsecond (μas). However, systematic effects and atmospheric turbulences prevent VLBI astrometry achieving such a high accuracies in phase-referencing observations at other frequency regimes. These effects can be cancelled out, only to a certain degree, if using calibrator sources close to the target object. This is illustrated in Fig. 1: under the assumption of an interferometer array with a maximum baseline of 3000 km (actually, very similar to the planned SKA2 realization), Martí-Vidal et al. [13] reported a complete study based on Monte Carlo simulations of the behaviour of the astrometric accuracy and sensitivity of the array as a function of the frequency and calibrator source separation. These authors found that the astrometric performance of such an array is optimum between 1 GHz and 10 GHz; out of this range, the accuracy is degraded by the ionosphere (lower frequencies) or the wet troposphere (higher frequencies). We show in Fig. 1 the difficulty to reach μas-accurate astrometry with an array similar to the SKA in resolution and sensitivity. Therefore, the application of conventional in-beam phase-referencing and Multiview techniques [6, 19], which minimize the astrometric errors as those shown in Fig. 1, appear essential to achieve accuracies close to the values given by σ_{th}. According to the Multiview techniques, with multiple simultaneous observations from different lines of sight it is possible to solve for a full 2D correction to the atmospheric distortions around the target, thereby providing significantly improved calibrations and enabling astrometric measurements. This configuration allows the use of calibrator sources with separations beyond the ionospheric patch size. Therefore, the Multiview approach allows one to select as calibrators well-studied sources which have been shown to be steady and compact at higher frequencies, addressing the issue of whether the reference position is stable in weak sources.

We show in Fig. 2 the behaviour of σ_{th}, i.e., the *maximum* accuracy attainable, for different configurations of SKA:

- **SKA1-mid**. Considering the present SKA Phase 1 design, the maximum baseline lengths will come from the SKA1-mid version, around 200 km, which are in principle certainly short if compared with the thousand-km size of present VLB arrays. Accordingly, even for substantial dynamic range and high frequencies, the accuracy would be limited to tenths of the milliarcsecond.
- **SKA1+VLBI**. To approach the μas accuracy, the resolution of SKA1 needs to be enhanced with the addition of VLBI stations to form longer baselines. In the case considered for Fig. 2, SKA1-mid is used as a hypersensitive phased-array within a VLBI network (in practice the array used to calculate the accuracy values extended the baseline lengths to 10000 km).
- **SKA2**. Alternatively to the previous item, the resolution can be improved by adding new antennas to the SKA1 configuration. This could be effectively done connecting electronically present VLBI stations to SKA1; however, the full development of this option will have to wait until completion of SKA2 realization, which will extend SKA1-mid spiral arms to baselines up to 3000 km. We have calculated the astrometric accuracy for this latter case.

SKA1 will have the capability for carrying out Multiview observations using the ability to form at least four independent pointed beams of phased-up VLBI outputs within the primary beam of a single antenna, which is ∼1 degree (i.e. multiple "in-beam" type calibrators). This type of observations are compatible with the capabilities of antennas from existing VLBI networks for joint observations with SKA1. Multiview with larger target-calibrator separations are possible with SKA1, using the capability for multiple tied sub-arrays (i.e. groups of antennas pointed simultaneously at different sources), although this is not widely available at other sites. On the other hand, with antennas equipped with phase array feeds (PAFs) spanning up to 3000 km baselines, planned for the SKA2 realization, any target-calibrator separation ("in-beam" type or not) for Multiview observations will be within reach.

In summary, for SKA in phase 1, the extraordinary continuum sensitivity, $\sim 1\,\mu$Jy for 1hr integration time, will allow astrometric studies at sub-mas level of a wide variety of objects well below the detection threshold of present VLB arrays. Significant improvements in astrometric accuracy, even in the most favorable configuration of array/source geometry (allowing either in-beam phase-referencing or multibeaming), necessarily will come from the SKA2 realization or combination of SKA1-mid with existing VLBI networks.

3 Science from SKA Astrometry

3.1 Stellar astrometry

Although mostly based on targeted observations, our present understanding of stellar radio emission comprises from young stellar objects until supernova remnants, going through virtually every stage of the stellar evolution [8]. SKA, in any of its realizations, will provide a comprehensive study of radio stars from well-defined samples, and many astrometric projects will benefit from a precise determination of the proper motion, parallax, and possible further perturbations of their trajectories. Here we mention only some of the possible projects.

Distances and the 3D structure of star forming regions in the solar neighborhood can be definitively established. Present surveys on the *Gould's belt* [11] could be extended to hundreds of stars on those regions accesible by the SKA (i.e. star forming regions in Ophiucus, Taurus, Perseus, Aquila/Serpens, and Lupus). Kinematics within these regions could be measured, of relevance to the understanding of stellar formation activity. Similarly, **distance to stellar clusters** could be defined with high precision. The Hyades and the Pleaides clusters have been used as reference in astronomical distances, from which the cosmic distance ladder is defined. However, the "Pleaides distance controversy" put into question the Pleiades distance derived by HIPPARCOS, different from the distance derived by other techniques [23, 16]. VLBI observations have shown the possibility to use radio stars to solve this important ambiguity [15]. The contribution of SKA will extend the distance determinations to other clusters which, in turn, will be also observed by Gaia, surely producing new "Gaia/SKA controversy" episodes that could be studied at the microarcsecond level.

Calibration of the stellar mass-luminosity relation, in special for pre-main sequence (PMS) objects, is relevant as this relation is profusely used to derive masses of stellar, and substellar objects. Many of the stars belonging to nearby clusters or moving groups are known to be double or multiple systems. SKA astrometry would be directed to determine or refine measurements of the distance and/or orbital motion of hundreds of stars (where RV methods might be hampered by the activity inherent to the radio emission). Taking into account that the age of these objects is precisely determined given their membership to known clusters, the dynamical masses obtained by successive SKA observations would impose strong constraints to stellar evolutionary models [4, 5]. This will specially relevant to alleviate the deficient observational status of dynamical masses of PMS stars [9]. The μas accuracy provided by **SKA1+VLBI or SKA2 would reveal low-mass objects, brown dwarfs or planets**, around the sampled stars, whose mass could be measured with high precision. The moving groups found in the vicinity of the Sun [22, 24] are specially well suited for this purpose with SKA: these associations are nearby (15–50 pc), young (5–100 Myr, favoring the possible radio emission of the host stars and –luckily– the low-mass companions [3]), and located well in the South (β Pictoris, Tucana-Horologium, TW Hydrae, Columba, Carina, Argus, and AB Doradus moving groups). Possible microarcsecond astrometric signatures present in stars members of these groups could be accurately sampled by the SKA, with capability to detect from a Jupiter-like planet around a $1\,M_\odot$ star at 50 pc ($100\,\mu$as signature) to an Earth-like planet around a $0.2\,M_\odot$ star at 15 pc ($1\,\mu$as signature).

3.2 AGN astrometry

Present VLBI arrays may reach μas accuracy in astrometric observations of pair of AGN cores with the appropriate geometry on the sky. SKA1+VLBI (and SKA2) will provide a similar (or superior) accuracy extending the application of astrometric techniques to micro-Jy level sources. Opacity effects near the AGN core, that translate to shifts of the core position as measured at different frequencies [14, 10], could be studied with high precision for a significant number of sources.

Interestingly, Gaia will provide optical positions for hundreds of AGNs with accuracies up to the microarcsec level that can be compared with those measured in radio; this will lead to relevant testing of AGN theories about the different location of optical and radio emission (i.e., the corona or disk of the black hole for the former, and last scattering surface of the jet for the latter). For the case of blazars, the class of radio loud AGN with powerful jets better oriented to the line of sight, the relative location of the multi-spectral-range emission region with regard to that at radio wavelengths has drastic consequences on the feasible high-emission (gamma-ray) regions [12]. Currently, estimates of the relative locations can be made for a small number of sources, by cross correlation of monitoring light curves at different wavelengths with those from particular jet knots identified on ultra-high resolution VLBI monitoring projects [1, 2]. The combination of high precision astrometric programs with SKA on large samples of blazar jets with the Gaia positions will provide the needed volume of data to make independent and robust tests on the relative location of the radio, optical, and even gamma-ray emission regions in blazars.

Additionally, the International Celestial Reference Frame (ICRF), defined by the radio positions of non-variable radio sources, should be tied to the future Gaia reference frame. Since AGNs are expected to be used for the alignment of the radio and optical frames, the understanding of the previous effects is essential.

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