Chapter in **Advancing Astrophysics with the SKA – II**

SKA VLBI survey of the Southern sky for astrometry, geodesy, and astrophysics

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The development of SKA will open the opportunity to run dedicated VLBI surveys of the Southern sky and observe sources not visible at radio telescopes located in the Northern hemisphere. These surveys will allow for doing geodesy with a Southern hemisphere-centered network, increase the density of compact radio sources that can be used as calibrators, further extend the celestial reference frame to deep south, and facilitate high-precision differential astrometry for a wide range of applications. Achieving a deep completeness level and determining the parsec-scale properties of extragalactic radio sources is crucial for multi-wavelength and multi-messenger astrophysics. This includes supporting Cherenkov and neutrino telescope science cases, as well as joint VLBI-Gaia studies of active galaxies.

https://skao.int/

1 Introduction

The most complete catalogue of compact radio sources derived from analysis of VLBI observations at centimeter wavelengths, that is available so far, is the Radio Fundamental Catalogue (RFC; Petrov and Kovalev, 2025), updated on a quarterly basis and available at https://doi.org/10.3847/1538-4365/ad8c36. By October 2025 the catalogue contained 21,949 objects. The RFC is based on analysis of all publicly available observations from absolute astrometry and geodesy programs. However, the catalogue has a significant disparity between declination zones $[-90°, -40°]$ and $[-40°, +90°]$: the density of compact radio sources listed in the RFC in the first zone is 644 objects per steradian versus 1988 objects in the second zone. Contribution to the RFC in the latter zone is almost exclusively based on observations from the Very Long Baseline Array (VLBA) located at the Northern hemisphere. The list of known sources with parsec scale-emission in $[-90°, -40°]$ originates from the VLBI geodetic program that started in 1980s (39 sources or 3%), CRF program (Fey et al., 2004) (22 sources or 2%), CRDS program (Weston et al., 2023) (182 sources or 13%), the Search for SOuthern Fermi Unassociated sources program (SOFUS) (L. Petrov, in preparation; 126 sources or 9%), and the Long Baseline Calibrator Surveys (Petrov et al., 2011, 2019) (1100 sources or 76%). Among 1447 objects in the RFC at declinations $< -40°$, 643 were detected at 2.3 and 8.4 GHz, and 804 objects (56%) detected at 8.4 GHz only. The SKA VLBI survey based on deep radio surveys of the Southern sky (e.g., Duchesne et al., 2025; Norris et al., 2011) will improve the completeness of radio calibrator catalogs such as the RFC.

In this chapter we discuss geodetic, astrometric, and astrophysical science cases as well as requirements for a deep targeted survey of compact extragalactic radio sources in the southern sky by an SKA VLBI system.

2 Geodesy

The technique of VLBI begun to be used for geodesy and astrometry in 1970, after its development in 1960s by astronomers for imaging radio sources. The first Southern hemisphere VLBI telescope was built at Hartebeesthoek, South Africa dedicated for geodesy in 1986, followed by the Hobart 26-meter telescope in Australia in 1989 and telescopes at O'Higgins, Antarctica and Fortaleza, Brazil in 1993. In 2010, three telescopes at Hobart, Katherine, and Yarragadee in Australia and one at Warkworth in New Zealand expanded the geodetic/astrometric VLBI network in the South.

Since 2019, the new generation geodetic VLBI system (see, e.g., Niell et al., 2018) has started to operate regularly to make geodetic and astrometric observations, currently with a network of 16 to 19 telescopes observing 24 hours once per week. Due to the asymmetric distribution of the telescopes between North and South — only four telescopes available in the South, the Southern telescopes have been less efficient than those in the North, e.g., the average number of observations per telescope is 1.5 to 4 times less for the southern telescopes. Given this asymmetric network, the geodetic/astrometric observations need to observe the radio sources in the Northern hemisphere more often than the South to acquire as many observables as possible.

SKA will enable for doing geodesy/astrometry with a Southern hemisphere-centered observing program and an improved sensitivity to observe much weaker sources than the current geodetic network can do. Figure 1 shows the radio telescopes that may join the SKA for VLBI observations. It will allow for the following research and applications in geodesy:

1. Determining the positions of the SKA telescopes in the global TRF and monitoring their velocities. This will allow for high accuracy differential astrometry with the SKA.

2. Reducing the dominant impact of Northern stations on the scale of terrestrial reference frame (TRF). Kern et al. (2025) claimed that the non-linear motion of VLBI station NYALES20 in Norway is responsible for more than 50% of the drift in the TRF scale as reported in Altamimi et al. (2023). The impact of one specific VLBI station in the far North on the global TRF can be mitigated by a geodetic observing network in the South.

3. Measuring the relative positions of the telescopes of the SKA-mid AA configuration with sub-mm accuracy. It was demonstrated (see, e.g., Xu et al., 2023) that resolving phase delays on the short baselines allows for sub-mm accuracy of station positions. This can be done for 254 SKA stations to link the array together.

4. Establishing the SKA array as the core geodetic station with respect to which the positions and motions of the other Southern telescopes are determined with higher accuracy. The TRF is established through geodetic observations dominated by the Northern hemisphere-centered network; there is no comparable observing network in the South so far. A regular observing program with the SKA as shown in Fig. 1 will improve the global geodesy.

5. Investigating the potential usage of the radiometers for the tropospheric turbulence. The atmospheric turbulence on the time scales less than 1 hour (to a few seconds) introduces delay errors of tens of pico-seconds, and it causes one of the major challenges to improve the geodetic accuracy. The water vapor radiometers at the SKA site in real-time tracking of VLBI observations will provide valuable data to investigate how to model these errors.

3 Calibration of SKA with co-located GNSS receivers

An array of a size of 180 km is a factor of 50 times smaller than a global array with baseline projection lengths up to 9,000 km, which is close to the practical limit of effectively scheduling VLBI observations. Considering the floor of the accuracy of VLBI absolute astrometry of 0.1–0.2 mas due to systematic errors (Petrov and Kovalev, 2025), we can expect an accuracy of absolute astrometry of 5–10 mas or better from the SKA if we will take the systematic errors into account. One of the major factors that affect accuracy of geodesy and absolute astrometry observations is residual errors of modeling path delay in the neutral atmosphere (see, e.g., Petrov et al., 2025) after solving for zenith path delay from the same radio interferometry observations. Several recent studies demonstrated that the effect due to the angular structure of the radio sources is one of the major systematic error sources (see, e.g., Anderson and Xu, 2018; Xu et al., 2021).

Source structure may have minimum effect on the observations from the SKA only. However, observations at an array of a size of 180 km are not favorable for a reliable estimation of the tropospheric path delay: the differences in elevations at different antennas do not exceed 1.5°, which makes estimates of zenith path delay and clock highly correlated. This high correlation is further extended to the parameter of station position in the astronomical observations, where the radio sources in a small or regional sky area are observed. This problem can be mitigated by the emerging technique of micro-VLBI successfully demonstrated in Skeens et al. (2023). If a permanent Global Navigation Satellite System (GNSS) antenna is deployed at a distance of 70–100 m of a radio telescope that is capable to record voltage in a range of 1.17 to 1.66 GHz — the frequency range of GPS, GLONASS, Galileo, and Beidou geodetic satellites, such an antenna can be used as an element of a radio interferometer with a radio telescope. Processing observations of GNSS satellites on an array consisting of GNSS antenna and radio telescopes allows us to determine fringe phase. After resolving phase delay ambiguities, the baseline vector connecting a radio telescope and a co-located GNSS antenna can be evaluated with a one millimeter accuracy. The feasibility of this approach has been proven by recent observations at VLBA and co-located GNSS antennas deployed in 2024–2025 (J. Skeens, in preparation). Such observations will tie a radio telescope of the SKA array to the terrestrial coordinate system realized by the ground network of GNSS antennas with a millimeter level of accuracy. Implementation of such ties at *every SKA station* effectively transforms SKA to an enhanced SKA+GNSS array. Furthermore, analysis of GNSS data from co-located antennas allows us to derive zenith path delays regardless of SKA data. The capability to estimate zenith path delay and position of elements of SKA antennas from observations of GNSS satellites using co-located GNSS antennas makes *a transformative impact* on the ability to derive absolute positions of radio sources. The method of absolute astrometry implies a simultaneous determination of the position and orientation of an instrument — in this case the SKA+GNSS array — and positions of radio sources as well as atmospheric path delays.

This micro-VLBI technique has a potential to contribute to geodesy directly. Installation of a permanent GNSS antenna on a deep drilled braced monument (see, e.g., He et al., 2025, and reference therein) makes a geodetic network of companion GNSS antennas suitable for monitoring changes in their positions due to tectonic motion and environmental effects with a sub-millimeter level of accuracy. Regular observations of GNSS satellites using the micro-VLBI technique will provide independent datasets, in addition to the phase delays of the SKA observations (see previous section), to measure relative motions of SKA antennas at a one millimeter level of accuracy with respect to the reference frame based on positions of GNSS antennas. The differences in the results from VLBI phase delays and the micro-VLBI technique can be investigated at the 1-mm accuracy level, which may provide understanding of the causes of the station position differences between group delay and phase delay.

Deployment of a permanent GNSS station within 70–100 meters away from each SKA radio telescope provides another advantage. Observations of dual- and triple- band GNSS satellites allows us to determine slant ionospheric path delays for calibrating the SKA observations with a single frequency. Nowadays, typically 40 to 50 satellites are visible at a given site and a given moment of time. Processing slant path delays due to ionosphere to 40 to 50 satellites from 254 planned SKA stations provides a large dataset that can be used for determination of time-varying biases in the Global Ionospheric Model (GIM). It has been demonstrated by Petrov (2023) that applying time-variable biases improves determination of the ionospheric path delay up to a factor of 3 with respect of the use of the GIM derived from analysis of a global network of GNSS antennas. This approach of refining GIM using slant ionospheric delay from co-located GNSS antennas can

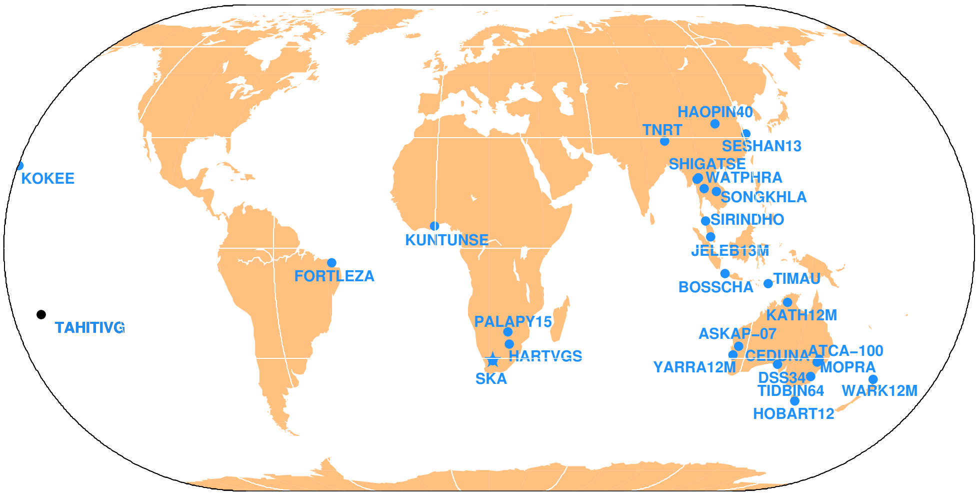

Figure 1: A Southern hemisphere centered network with SKA. At Tahiti site, indicated by a black dot, there is a plan to build a quad-band telescope as one of the geodetic stations while at the other sites radio telescopes are already available (either operating or under signal chain tests).

be further extended to a development of a regional ionospheric model that will help to mitigate the impact of residual ionospheric delays on SKA astrometry in the case of astronomical observations with a single frequency.

4 Astrometry

In the context of this article, astrometry refers to absolute astrometry that uses the observable of the total delay derived from the cross correlation of the radio signals to determine positions of radio sources, station positions, Earth orientation parameters, and some calibration parameters simultaneously in a single solution. In contrast, differential astrometry uses the observable of the differential (phase) delay among the objects (including targets and calibrators) in a small sky area to mitigate the common systematic errors and determines their position differences — the positions of the targets can thus be derived if the positions of the calibrators have been determined from absolute astrometry programs.

For the high accuracy astrometry beyond the current capability, it requires modeling the effects due to structure of the radio sources in group delay observables because source structure causes astrometric positions to change along the jet direction over time and over frequency (e.g., Petrov and Kovalev, 2025; Xu and Charlot, 2025). This eventually brings geodesy, astrometry, and astrophysics together. For the same VLBI experiment, radio images can be derived and then used as source models in the geodetic data processing to derive astrometric positions that are free of these effects. It will allow for directly registering the absolute astrometric position on the radio image, and thus for the identification of the location of the optical emission as measured by Gaia. In these VLBI observations, a limited (but reasonable) number of sources can be observed in each 24-hour experiment to have a reasonably good sky coverage every one hour for estimating tropospheric delays and to have a good uv coverage for each source to obtain the images.

5 Astrophysics

There are numerous astrophysical applications that require deep, complete, all-sky samples of VLBI-selected extragalactic radio sources, or a high density of compact calibrators enabling phase-referencing observations of weak targets. These include:

1. Reconstruction of the Galactic scattering screen properties (Koryukova et al., 2022);
2. Studies of VLBI–Gaia position offsets, which trace synchrotron opacity effects and electron re-acceleration sites in relativistic jets (Kovalev et al., 2017; Plavin et al., 2019; Fichet de Clairfontaine et al., 2025);
3. Identification and investigation of Compact Symmetric Objects (e.g., Kiehlmann et al., 2024);
4. Identification and characterization of AGN producing high and very-high-energy γ-rays (e.g., Kovalev, 2009; Petrov and Kovalev, 2025; Piner and Edwards, 2018);
5. Identification and study of potential astrophysical neutrino sources (e.g., Plavin et al., 2023; Kovalev et al., 2025);
6. A search for and characterization of new strong gravitational lenses (Treu, 2010; McKean et al., 2015);
7. Precision differential astrometry, including pulsar and maser parallax measurements, time-domain VLBI, and transient sky studies requiring phase-reference calibrators (e.g., Reid and Honma, 2014; Deller et al., 2019; Marcote et al., 2020).

6 Summary

VLBI observations with the SKA, supported by the co-located GNSS antennas and water vapor radiometers, allow for a wide variety of scientific applications for geodesy, astrometry, and astrophysics. The SKA will open unique possibilities in these fields because of its geographical location and the high sensitivity.

Global geodetic and astrometric VLBI observations with the SKA need to be carried to tie the positions of the SKA telescopes to the global terrestrial reference frame and measure the positions of the radio sources for the improved accuracy. To measure ionospheric-free group delay precisely that is needed for geodesy and astrometry, two or more frequency bands with separation of a factor of larger than 1.7 and with a broad bandwidth per band (> 0.5 GHz) should be used.

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