# Spatio-kinematical structure of the Galactic Nuclear Stellar Disk revealed in VLBI astrometry of circumstellar masers

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SKA-VLBI astrometry will enable us to measure up to thousands of three-dimensional motions of OH masers associated with circumstellar envelopes (CSEs) of OH/IR stars in the Nuclear Stellar Disk (NSD) and sites of high-mass star formation in the Central Molecular Zone (CMZ) of the Galactic Center (GC). It is expected that the spatio-kinematical distribution of those OH masers should indicate the existence of a ring structure in the NSD, which has formed as a result of outward propagation of star-formation activities in the GC. This is likely visualized clearly by a group of OH/IR stars, some of which should have stellar pulsation periods of >400 days and the corresponding ages of <500 Myr, and some sites of ongoing star formation. These OH/IR stars should host 1612-MHz OH masers, some of which should become targets of huge-sample VLBI astrometry, in moderate accuracy, in SKA-MID Band 2 (∼1.6 GHz). The data of maser source proper motions will exhibit a stream motion in the stellar ring structure. Furthermore, the information of accurate distances (error <100 pc) of the maser sources are necessary to directly find the major-axis direction of a possible elliptical ring of stars at ∼8 kpc. These distances may be yielded through trigonometric parallaxes measurable in SKA-MID Band 5a (5–7 GHz) and/or photometric parallaxes derived from the pulsation period–luminosity relation of long period variable stars hosting the maser sources.

 

## 1 Introduction

High accuracy radio astrometry such as the VLBI projects conducted with VERA, VLBA, EVN, and LBA have revealed directly the three-dimensional, spatio-kinematical structure of the Milky Way Galaxy (MWG) by targeting sources of astrophysical masers from excited molecules such as $CH_3OH$, $H_2O$ and SiO, and compact non-thermal continuum sources including pulsars for *the Galactic trigonometry* (see some reviews, e.g., Reid et al. 2019; VERA Collaboration et al. 2020). However, despite such projects dedicated on VLBI astrometry, the number of target sources has been limited to ~300 (e.g., Reid 2024). This number limit has been attributed mainly to the sensitivity and the fields of view to observe simultaneously the targets and calibrators. Higher precision (up to several $\mu$as) astrometry has been possible in a higher frequency band yielding higher angular resolution, such as 22 and 43 GHz covering $H_2O$ and SiO masers, respectively (and $CH_3OH$ masers at 6.7 and 12.2 GHz). In a lower frequency band, such as 1.6 GHz covering OH masers, the astrometric precision is improved with higher sensitivity, but the VLBI data are significantly affected by the Earth's ionosphere and the intrinsic structures of the target and reference sources (see a review of Rioja and Dodson 2020). Nevertheless, astrometry at such a low frequency still fascinates us because some sources such as OH masers, the main targets in this chapter, should provide key opportunities for exploring stellar physics and the spatio-kinematical structure of the inner part of the MWG in the era of SKA with VLBI capability.

This chapter focuses its main scientific interests in VLBI astrometry of OH masers in the Galactic Center (GC), including the Nuclear Stellar Disk (NSD) whose radius is ~200 pc (e.g., Nishiyama et al. 2013), and comparable to that of the Central Molecular Zone (CMZ, e.g., Sofue et al. 2025). Section 2 describes the background and the motivation of this science case with the SKA (see also Rygl et al. 2026; Rioja et al. 2026). Section 3 demonstrates the scientific feasibility of the huge-sample astrometry of circumstellar OH maser sources in the NSD. Section 4 demonstrates the technical and operational feasibility of such astrometry in the era of SKA-VLBI. Here we consider SKA-VLBI as a VLBI array that is composed of the SKA providing multiple high-sensitivity beams from its tied-array and remote VLBI stations yielding a variety of baselines from several 10 km with the SKA's arm stations up to several 1000 km with international stations.

## 2 The NSD and CMZ hosting OH masers

The MWG is confirmed to be a barred spiral galaxy, in which gas fueling into the GC has been triggered by the bar-shaped gravitational potential (e.g., Kumar et al. 2025). Particularly, active star formation triggered by such bar fueling is expected to form the NSD and this will be observed directly from the orbits of stars in this region (Baba and Kawata, 2020). Fig. 1 shows the NSD visualized on basis of the simulation results by Baba et al. (2017), which exhibits a ring-shaped distribution of stars born within 400–500 Myr. Although precisely determining the distances from the Sun to the individual stars in the GC is challenging (e.g. Oyama et al. 2024), the proper motions of these stars only may emerge a stellar stream along an elliptical ring structure as demonstrated in the right panel of Fig. 1. Baba and Kawata (2020) also suggest the importance of the proper

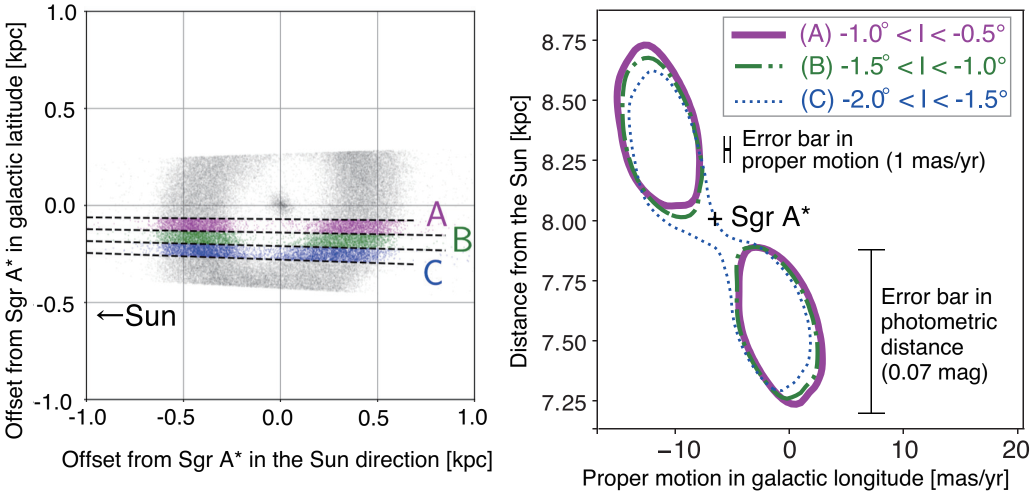


**Figure 1:** *Left*: Face-on view of the distribution of stars within ages of 400–500 Myr in the NSD, which is reproduced with the output data of the simulation by Baba et al. (2017). The plotted star distribution is limited to the range of galactic longitude $-3° \leq l \leq 2°$. Three areas, A, B, and C, are defined accordingly for the three directions of galactic longitude. *Right*: Proper motions of stars in galactic longitude. 90% of stars in each of the areas A, B, and C are included in each enclosed area.

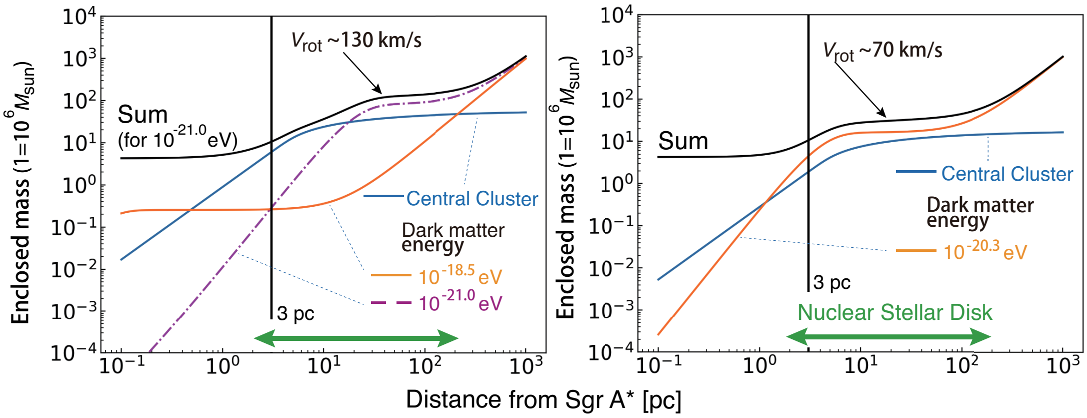


**Figure 2:** Mass distribution models within 1 kpc of the GC depending on energy of a dark matter particle and their mass distribution in the GC presented by Toguz et al. (2022). The displayed figures are edited from the original forms in the paper. The total enclosed mass, which is observationally indicated by the rotation speed, is set to equal between the models within 2 pc of Sgr A* as already observed (Schödel et al., 2009) and at 1 kpc from Sgr A* regardless the energy of each dark matter particle ($10^{-18.5}$, $10^{-20.3}$, $10^{-21.0}$ eV in the panels) dominating the total mass of the NSD. On the other hand, the enclosed mass and the rotation speed may change by a factor of ~2 in the NSD. The difference in the rotation velocity is measurable from 3D velocities of stars, which should be corrected for deviations from circular motions.

motions for reducing contamination from other, kinematically hotter stars, such as those from the Galactic bulge, bar, and disk.

The rotation curves of the MWG, especially on the scale of the NSD (10–200 pc), also probes the distribution and the character of the dark matter in the GC. Fig. 2 shows the MWG rotation curves and the enclosed mass in a few cases with different particle energies of the ultra-light dark matter (ULDM) described by Toguz et al. (2022).

Although plenty of line-of-sight velocity information, as well as evolution and metallicity tracers, of stars and gas is nowadays available, the information of stellar proper motions is indispensable in order to extract the components that are dynamically associated with the NSD and the CMZ. Therefore, it is crucial to select samples of stars that are really associated with the system and trace the history of star formation in the system. The sample of $H_2O$ and $CH_3OH$ maser sources associated with the sites of present star formation is much limited, such as Sgr B2, implying inactive star formation in the present CMZ. The measurement of the precise secular 3D motions of the interstellar maser sources is also challenging because these motions are significantly affected by the internal motions of the clusters of maser features associated with (high-speed) outflows (e.g., Sakai et al. 2023).

On the other hand, there exist hundreds of circumstellar OH (mainly at 1612 MHz) and SiO maser sources currently confirmed toward the GC. Deep and unbiased surveys of maser sources have been conducted toward small areas around (within 20″–0.4°or 0.8–60 pc of) Sgr A* (e.g., Sjouwerman et al. 1998, 2002). Compared with ≥6 000 stars within 1 pc of Sgr A* with measured proper motions (Schödel et al., 2009), the number of stars whose proper motions are determined in SiO maser astrometry is quite limited (≤35, Tsuboi et al. 2025). In wider sky areas corresponding to the NSD, SiO maser surveys have been conducted, yielding hundreds of detections towards targeted infrared stars (e.g., Deguchi et al. 2004; Fujii et al. 2006; Tsuboi et al. in private communication). Note that the Bulge Asymmetries and Dynamic Evolution (BAaDE) survey (Sjouwerman et al., 2024) covered a larger area and targeted ∼28 000 stars, but yielded a limited number of maser detections in the NSD. We note the pioneering work by Lindqvist et al. (1992), who demonstrated the NSD rotation using a sample of ∼130 OH/IR stars.

Here it should be highlighted that these masers are associated with long period variable stars (LPVs), many of which have been identified through infrared photometry (e.g., Glass et al. 2001; Matsunaga

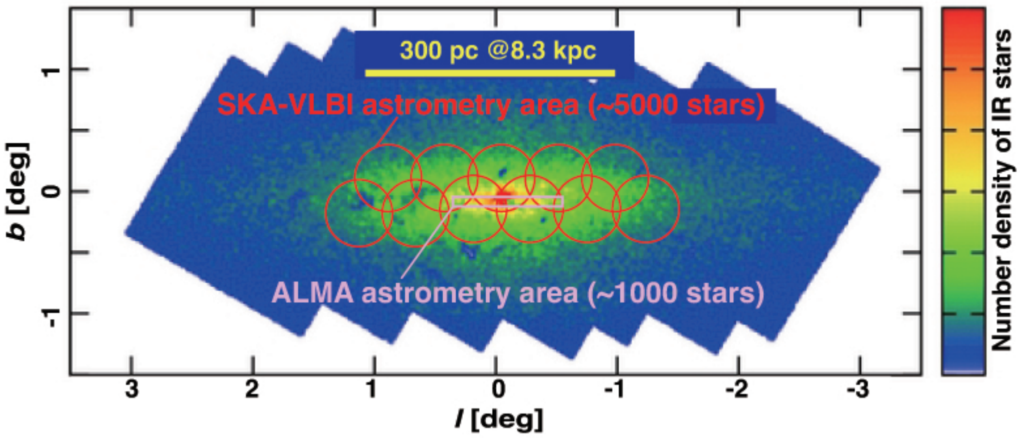


**Figure 3:** Areas of the SKA-VLBI astrometry toward the NSD. A red circle indicates the field of view or the single-dish beam of SKA-MID Band 2 (∼0.5°) in the VLBI astrometry, which covers a region of a moderate stellar density shown in the background colored map of the number density of near-infrared stars (Nishiyama et al., 2013). For comparison, a magenta box indicates the area of the ALMA astrometry that aims to measure ∼1000 proper motions of SiO maser sources within a field of currently realistic, general observation programs.

et al. 2009). The "multi-epoch infrared VISTA Variables in Via Lactea (VVV)" survey (Sanders et al., 2022) has identified 1782 LPVs in an area of $3 \times 3$ deg$^2$ of the GC. The ages of these LPVs may be well determined in their period–age relation (e.g., Trabucchi and Mowlavi 2022), in which stars with $P \gtrsim 400$ days may have $t_{\rm age} \lesssim 500$ Myr. Such LPVs often host SiO masers (e.g., Deguchi et al. 2004). Note that OH masers are also hosted by such LPVs although their detection rate is lower than that of SiO masers (Deguchi et al., 2004). OH maser source surveys recently conducted will be deeper and cover wider sky areas than the previous ones mentioned above, such as the GASKAP-OH (Galactic ASKAP spectral line survey for hydroxyl, Dawson et al. 2024), so as to detect thousands of OH masers.

Fig. 3 shows the survey area of circumstellar OH maser sources described in this chapter. Extrapolating the result of the recent SiO maser astrometry with ALMA in a small area around Sgr A* (Tsuboi et al., 2025), one can estimate to measure ~1000 proper motions of SiO masers in a larger area shown in Fig. 3. If the astrometry of OH masers is conducted in an area ~20 times as large as that for SiO masers, proper motions of up to ~5000 OH masers may be measurable. Taking into account the SKA-VLBI beam (~3″) much smaller than the single beam of the SKA-MID antennas or the field of view in the source finding surveys (~0.5°), the targets of the VLBI astrometry should be selected effectively after the surveys.

## 3 Huge sample VLBI astrometry of circumstellar OH masers in the NSD

The above consideration on the measurement of OH maser proper motions supposes OH masers brighter than 50 mJy at a detection over 7-$\sigma$ (here $\sigma$ is an rms noise level) in VLBI baselines ($\gtrsim$5000 km) as a target of the SKA-VLBI astrometry. This level of sensitivity is comparable to or a little higher than those toward the GC in the previous VLA/ATCA survey (Sjouwerman et al., 1998) and the ongoing GASKAP-OH survey (Dawson et al., 2024) when assuming a velocity width of ~1 km s$^{-1}$. Here we discuss the sensitivity of SKA-VLBI that should be feasible for the VLBI astrometry. Based on the output of *the SKA-MID Sensitivity Calculator*, we assume an SEFD~4 Jy at 1.6 GHz (Band 2) in the AA4 phase for the phased-up SKA-VLBI beams, around the middle between those in the AA* and AA4 phases. Note that the difference between the SEFDs assumed here and in the AA4 phase is attributed to the sub-arrays simultaneously observing calibrators together with the targeted OH masers in the Multi-View (MV) technique (Rioja and Dodson, 2020) mentioned later. As possible remote VLBI stations, we here suppose the 26-m telescope in Hartebeesthoek, South Africa (SEFD=430 Jy), 65-m in Sardinia, Italy (~100 Jy at an elevation of ~20°), 32-m in Noto, Italy (~900 Jy at $EL$ ~25°), 40-m in Chiang Mai, Thailand (~100 Jy), 26-m in Hobart (~500 Jy) and ATCA (~80 Jy) in Australia although other EVN antennas also may be available. Assuming a bandwidth of 5 kHz (≃0.9 km s$^{-1}$) for OH maser detection and 2-bit quantization in signal recording, we calculated the 1-$\sigma$ noise level to be ~10 mJy in integration of 1.5 hours and ~7 mJy in 3 hours. The integration for ~3 hours may be realistic in the SKA-VLBI toward the GC because of the sub-array capability of the SKA-VLBI and the common sky toward the GC with the remote stations. In this case, with a signal-to-noise ratio of ~7-$\sigma$, thermal limits will give ~1 mas accuracy astrometry.

In order to cover the fields of astrometry (11 single 15-m antenna beams) as shown in Fig. 3, one will need 11 VLBI observation sessions per year, each for a single 15-m antenna beam tracked for ~4 hours (including overhead of ~1 hour). Planning a project of 5 years for visiting each field in 5 times, one will request 220 hours in total. Thus, proper motions of OH masers may be determined in accuracy of ~0.3 mas yr$^{-1}$ (~10 km s$^{-1}$ at the GC), sufficient for finding the spatio-kinematics of the NSD predicted in Fig. 1 and 2. However, note that the SKA-VLBI beam is tiny (~3″) as already mentioned; therefore, one will request simultaneously multiple SKA tied-array beams towards the OH masers. Eventually, the total number of OH masers targeted for VLBI astrometry will be severely limited and proportional to the number of the SKA tied-array beams simultaneously available in narrow widths of base-band channels.

As long as a single field of view is tracked continuously over 3 hours, this project may have flexibility for joining commensally with other surveys toward the GC. Even in running alone the astrometry project proposed here, using all the available SKA antenna is essential for mapping the whole regions of circumstellar OH masers in high dynamic range, covering the emission extended up to ~1″(~8000 au at the GC). In fact, the angular size of the emission region can be compared with a linear size of the emission along the line of sight to derive geometrically the distance to the OH maser source (so-called phase-lag method, van Langevelde et al. 1990). The luminosity distances to the targeted LPVs hosting the OH masers may also be determined by combination of the data of infrared-photometry such as VVV (Sanders et al., 2022) and trigonometric parallax distances to the LPVs in the solar neighborhood for providing their precise $P$–$L$ relation in the MWG (Nakagawa et al., 2024).

## 4 Feasibility of high precision VLBI astrometry of OH masers

VLBI trigonometry has been conducted for circumstellar OH masers nearby the Sun (e.g., van Langevelde et al. 2000; Orosz et al. 2017). The results of such OH maser astrometry in early time were affected by the Earth's ionosphere and the accuracy has been limited to ~1 mas. Rioja et al. (2017) proved that the MV technique is really feasible to improve the precision of OH maser astrometry. If this technique is fully applied to the SKA-VLBI project proposed here, some of the OH masers (~10 even in the small area covered by Sjouwerman et al. 1998) brighter than 800 mJy may be the target for trigonometry in 10-$\mu$as accuracy (Rioja and Dodson, 2020; Rioja et al., 2026). Even the maser proper motions in 1-mas yr$^{-1}$ accuracy may better determine the rotation curve of the MWG on the NSD scale (Fig. 2).

Table 1 gives the list of the possible reference sources that are catalogued in the *VLBI Calibrator Search*[1] as of 2026 March and have unresolved flux densities (in a baseline length of 20 M$\lambda$ or 2500 km in S-band) higher than 20 mJy in S (2.3 GHz)-, C (5.0 GHz)-, or X (8.4 GHz)-band, suitable for L (1.6 GHz)-band VLBI astrometry. Fig. 4 shows the distribution of these sources, which well bracket the target area of the astrometry (Fig. 3) realizing the MV technique.

We find 4 compact S-band continuum sources catalogued within 2°.5 of Sgr A*, which have some

[1]http://astrogeo.org/calib/search.html

**Table 1:** Reference source candidates around the astrometric survey field.

| ID | Name | R.A. (J2000.0) | Decl. (J2000.0) | Detected band |
|---|---|---|---|---|
| 1 | J1745−2820 | 17:45:52.494523 | −28:20:26.28551 | XK |
| 2 | J1752−2956 | 17:52:33.108069 | −29:56:44.91563 | SX |
| 3 | J1752−3001 | 17:52:30.950082 | −30:01:06.68422 | SX |
| 4 | J1743−3058 | 17:43:17.886798 | −30:58:18.65557 | SCX |
| 5 | J1736−2737 | 17:36:10.177651 | −27:37:20.22288 | CX |
| 6 | J1754−3031 | 17:54:56.768512 | −30:31:44.12038 | SCX |
| 7 | J1756−2807 | 17:56:49.656940 | −28:07:37.67697 | S |
| 8 | J1758−3029 | 17:58:22.651936 | −30:29:15.79542 | CX |
| 9 | J1731−3003 | 17:31:46.851363 | −30:03:08.95426 | CX |
| 10 | J1751−2524 | 17:51:51.262535 | −25:24:00.06409 | SCX |

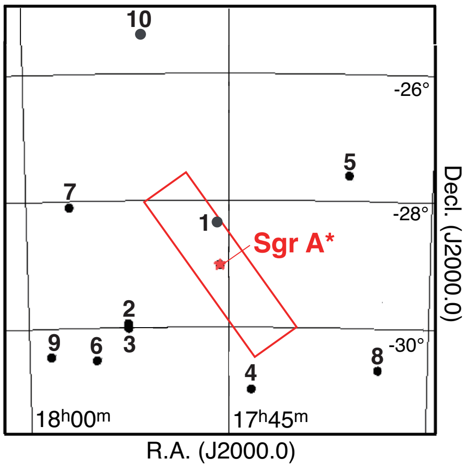


**Figure 4:** Distribution of the possible reference sources around the field of the planned SKA-VLBI astrometry toward the NSD. The IDs of the reference sources are listed in Table 1. The area of the astrometry is roughly drawn in a red box.

unresolved flux densities but do not well bracket even Sgr A* alone. In order to find such compact sources that well bracket the astrometry field, we need a separation angle of up to 5°.5 from Sgr A*. In this case, we find 10 compact sources detected in either S- or X-band. Thus the MV technique is essential to cover a relatively large separation angle (up to 7°) between the calibrators.

Here note that circumstellar OH masers have their large intrinsic sizes mentioned in Sect. 3 and those towards the GC are also affected by strong interstellar scattering (van Langevelde et al. 1992 and the references therein). Although some of the individual velocity components of OH masers located closely to the Galactic mid-plane are spatially unresolved in VLBI (e.g. Imai et al. 2013), we need VLBI baselines including the SKA tied-array with moderate lengths (~1000 km). Such SKA-VLBI baselines will be available with only Hartebeesthoek in the early phase of the SKA. Therefore, our science case described here focuses the main goal on measurement of a limited fraction of proper motions of the OH masers detectable with the SKA.

Higher precision of astrometry is expected in higher frequency bands such as SKA-MID Band 5a (5–7 GHz), Band 6 (~22 GHz), and 7 (~43 GHz) for circumstellar OH (~6.0 GHz), $H_2O$ (~22 GHz) and SiO (~43 GHz) masers. SKA-MID Band 6 and 7 will be available in the future SKA Observatory Development Program. If trigonometric parallax distances of the maser sources are determined for tens of stars hosting those masers in an accuracy better than ~100 pc, it may be possible to directly find the major-axis direction of a possible elliptical ring of stars at ~8 kpc (see

Fig.1).

However, the fields of view are smaller and the coherent times are shorter than those in Band 2, which should be taken into account for operation of remote stations that may need fast antenna nodding for source switching. Therefore, the target sources for such astrometry should be carefully selected in the bright OH maser sources in Band 2, to which the demonstration of the trigonometry may be still possible with the data set of the proper motion measurement.

Finally, the authors emphasize that the AA* phase should be a key to technically demonstrate any issue in the VLBI astrometry proposed here, starting with the beam that includes the calibrator candidate closest to Sgr A*, J1745−2820, and the survey area of OH masers (see Fig. 4). Involvement of the future African VLBI Network, including the Ghana 32-m telescope that is recently operational in scientific observations (Proven-Adzri et al. 2026), also will improve the astrometric accuracy.

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