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Past, present, and future of VERA

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Abstract. We constructed the Japanese VLBI network VERA (VLBI Exploration of Radio Astrometry) in early 2000s, which consists of four 20-m antennas with the maximum baseline length of 2300 km. The primary goal of VERA was to determine the 3D structure of the Milky Way Galaxy through VLBI astrometry by measuring trigonometric annual parallaxes and proper motions of Galactic radio sources up to 10 kpc distances. For this purpose, we developed the unique dual-beam receiving system with which target Galactic (mostly 22 GHz H_2O and 43 GHz SiO maser sources) and reference extra-galactic sources with separation angles within 2.2 degrees can be observed simultaneously. VERA as the Galactic astrometry project was completed in 2020 and the resultant catalog paper was published. Currently, VERA is open for VLCOP (VERA Large-scale Collaborative Programs) mainly led by the Japanese domestic communities contributing to array operation and instrumental developments. VERA has been collaborating with the Korean VLBI Network (KVN) just after the construction of both arrays in mid-2000's, and regular common-use observations have been conducted with KaVA (KVN and VERA Array) since 2014. Furthermore, some Chinese telescopes have been contributing to establish EAVN (East Asian VLBI Network), and it has also been open for common-use programs since 2018. For the future plan, we are considering possibilities to expand collaborations with other networks such as South-east Asian VLBI Network, EVN, Global VLBI Alliance (GVA), and SKA-VLBI.

1. Introduction

VLBI Exploration of Radio Astrometry (VERA) is a Japanese VLBI network operated by Mizusawa VLBI Observatory in National Astronomical Observatory of Japan (NAOJ), under collaboration with Kagoshima University. It has been constructed in early 2000 and started regular operation in 2003. The VERA array is consisted of four 20 m radio telescopes with the baseline lengths ranging from 1000 km to 2300 km (Fig. 1), which provide the synthesized beam size of 1.2 milli-arcseconds (mas) and 0.7 mas at 22 GHz (K-band) and 43 GHz (Q-band), respectively. As the project name explicitly suggests, VERA aims to conduct accurate VLBI astrometry in the radio wavelengths to measure annual trigonometric parallaxes and proper motions for the Galactic maser sources (Reid & Honma 2014, Rioja & Dodson 2020). VERA is designed to optimize observations of the 22 GHz H_2O masers or 43 GHz SiO masers with the dual-beam receiving system, with which both the target maser source and position/phase reference source (extra-galactic continuum source) within 2.2 degrees can be observed simultaneously at K- and Q-bands (Honma et al. 2008).

The first VERA astrometric results for parallax measurements were published in 2007 (Honma et al. 2007, Hirota et al. 2007) for the 22 GHz H_2O masers in star-forming regions, and all the astrometric observations with VERA up to 2020 were compiled in VERA Collaboration et al. (2020). Some other key papers were published in the special issues of VERA in the Publications of the Astronomical Society of Japan (PASJ) in 2008, 2011, 2014, and 2020.

2. Sciences

The main goal of VERA is to construct the 3-dimensional velocity and spatial structures of the Milky Way Galaxy through accurate VLBI astrometry of Galactic maser sources (Honma et al. 2012, 2015, VERA Collaboration et al. 2020), at the highest accuracy for the annual parallax measurement of $\sim$10 mas levels for the $\sim$10 kpc sources (Nagayama et al. 2020). The target sources are the 22 GHz H_2O masers and 43 GHz SiO masers located in star-forming regions and evolved stars (see Nakagawa et al. in this volume). Very Long Baseline Array (VLBA) legacy program, The Bar and Spiral Structure Legacy (BeSSeL) Survey, has been conducted similar studies (Reid et al. 2009, 2014, 2019) at almost the same period. These results have improved estimated values of the fundamental Galactic parameters such as the distance to the Galactic center and the rotation velocity of the Solar system. The results of these VLBI astrometry surveys are summarized in Table 1. In the most recent result from VERA Collaboration et al. (2020) compiled 224 maser sources measured mainly by VERA and BeSSeL, in which 99 of them are from VERA. Based on these results, we have constructed the rotation curve of the Milky Way Galaxy at the Galactocentric distance up to 15 kpc (Fig. 2)).

The estimated Galactic center distance, R_0 is consistent with those derived from the infrared astrometry of stellar orbits around the Galactic Center Sgr A* (Do et al. 2019, GRAVITY Collaboration et al. 2019, 2021). We note that the Gaia project provides a huge amount of astrometric survey data (Gaia Collaboration et al. 2023). However, the VLBI astrometry data are still complementary to opti-

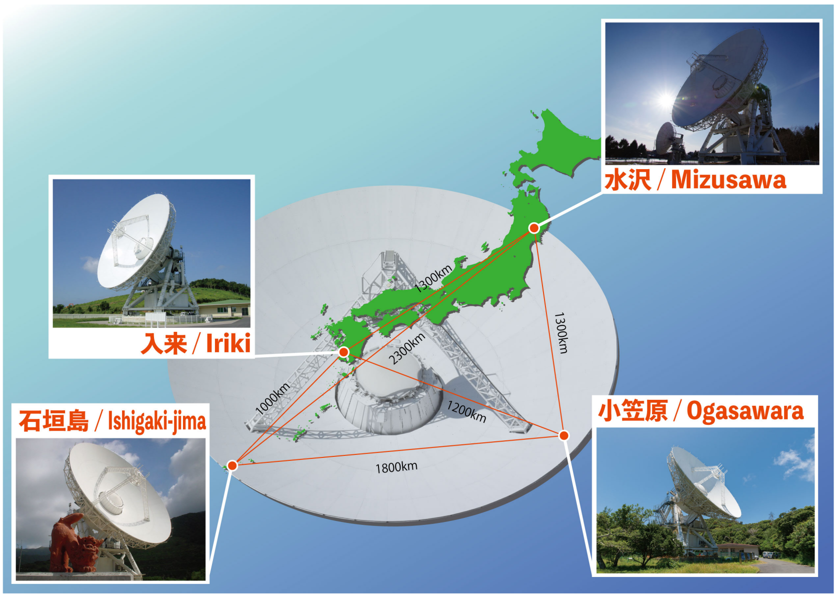

Fig. 1. Array configuration of VERA (NAOJ).

cal and infrared astrometry projects by enabling distance and proper motion measurements for farther and more deeply embedded sources in the Galactic disks, molecular clouds, and circumstellar envelopes (e.g. see Dzib et al., Nakagawa et al., and Plavin et al. in this volume).

3. Developments

VERA has been continuing system upgrade to improve observing sensitivities. For example, we have upgraded the digital back-end system to enhance recording rate from 1 Gbps (bit-per-second) to 2 Gbps, 4 Gbps, 8 Gbps, and 16 Gbps (Oyama et al. 2016, 2024). With the 2 bit sampling, we can achieve the total bandwidths of 4 GHz (i.e. 16 Gbps mode) at maximum, which enhances the sensitivities for the continuum observations by a factor of 4 compared with the nominal 1 Gbps observation. As a result, we could improve the signal-to-noise ratios for the continuum observations of Sgr A*, in particular for the longer baselines, and hence, provide accurate proper motion and tentative detection of the annual parallax (Oyama et al. 2024), as shown in Fig. 3.

The wide-band receiving system of VERA has also been applied to measure the polarization of the active galactic nuclei (AGNs). VERA succeeded in measuring the in-band Faraday rotation of AGNs at K-band, and solving ambiguities in the 2π rotation of the magnetic field vectors determined from band-to-band measurements between K- and Q-bands (Takamura et al. 2023).

It is crucial to enhance capabilities of VLBI correlators to process wide-band recording data. For this purpose, VERA has been continuing in-house development of both the CPU software correlator and more recent GPU correlator, which is under commissioning. The new GPU correlator enables to accelerate correlation at higher processing speed than the CPU correlator by a factor of $\sim$8.

Furthermore, we have installed receivers for 6.7 GHz (C-band) to cover the 6.7 GHz methanol maser transition and K/Q-band simultaneous receiving system, which are open for the common-use programs of East Asian VLBI Network (EAVN). We are also developing new 86 GHz (W-band), 1.5 GHz (L-band), and wide-band 6–18 GHz (C/X/Ku-bands) receivers. These are used for pilot studies and/or common-use programs for the present and/or future VLBI networks (see Section 5).

4. Current status

VERA has been participating to EAVN, consisted of VERA, some other antennas of Japanese VLBI Network (JVN) operated by universities, Korean VLBI Network (KVN), and Chinese VLBI Network (CVN) from the beginning in 2005, when the Korea-Japan VLBI collaboration of the KVN and VERA Array (KaVA) has been initiated (see Akiyama et al. 2022, Cui et al. 2023, and Wajima et al. in this volume). Common-use observations of KaVA and EAVN have been started in 2014, and 2018, respectively.

In 2021, the Galactic astrometry project of VERA has been completed and large-scale astrometric monitoring of maser sources has been finished (VERA Collaboration et al. 2020). Now VERA is used for common-use observations of EAVN and VERA stand-alone programs including single-dish usage and developments/commissioning for new observing systems. For the latter, the VERA array has started new operation mode to promote VLBI-related sciences mainly for the Japanese domestic communities from 2022, which is named as VERA Large-scale COllaborative Program (VLCOP). VERA allocates the observing times for the VLCOP proposals in exchange for contributions to observatory operations, such as in-kind contributions for array operation duties and devel-

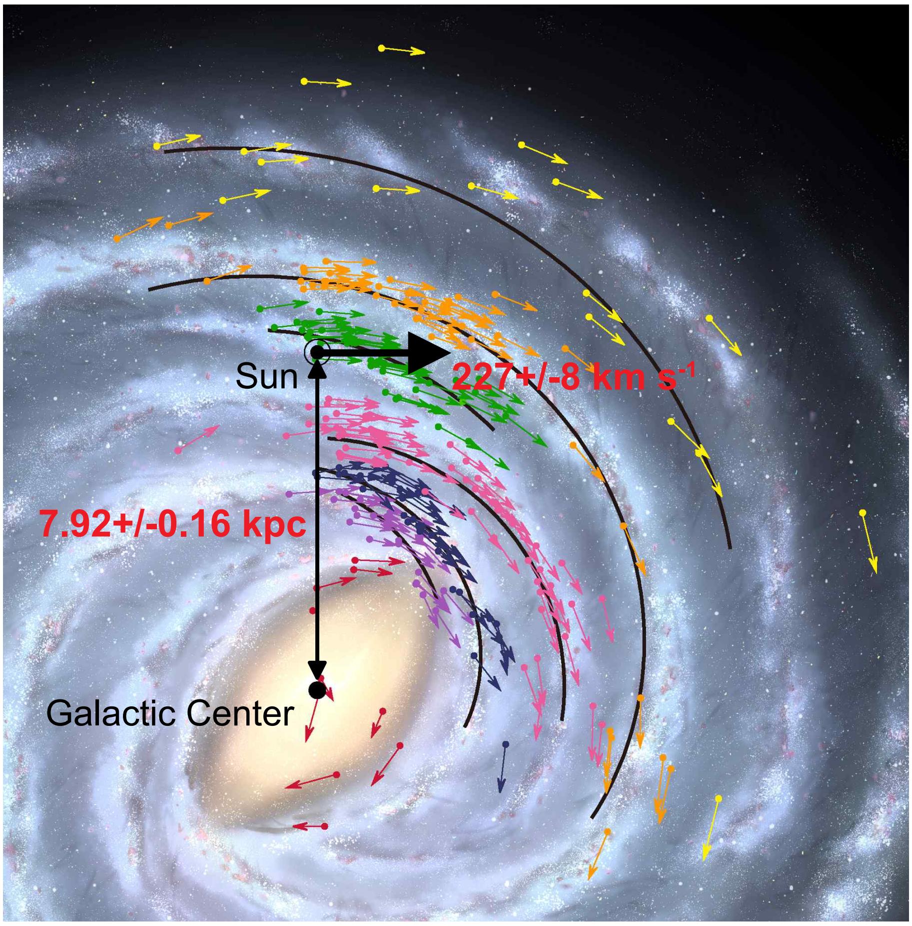

Fig. 2. An artistic image of the face-on view of the Milky Way Galaxy. Distributions of the maser sources measured with VLBI are plotted with arrows. Black solid lines show the spiral arm structure estimated from the BeSSeL results (Reid et al. 2019). The Galactic center distance, R_0, and rotation velocity, Θ_0, determined by the VERA project (VERA Collaboration et al. 2020) are also written in the figure.

Table 1. Galactic constants determined by VLBI astrometry

Parameter	Reid et al. (2009)	Honma et al. (2012)	Reid et al. (2014)	Reid et al. (2019)	VERA Collaboration et al.(2020)
$N_{\rm source}$	18	52	103	200	224[a]
R_0 (kpc)	8.4 ± 0.6	8.05 ± 0.45	8.34 ± 0.16	8.15 ± 0.15	7.92 ± 0.16
Θ_0 (km s^{-1})	247 ± 16	238 ± 14	240 ± 8	236 ± 7	227 ± 8

[a] 99 from VERA

opments/commissioning works. The telescope times for VERA were approximately 1000 hrs and 2000 hrs for the EAVN common-use and VLCOP, respectively. In addition, about 1500 hrs in total (sum of the VERA 4 stations) were provided for single-dish observations and developments/commissioning works at each of VERA station. Through the VLCOP framework, large programs for VLBI observations are being conducted such as long-term astrometry monitoring of Sgr A* (Oyama et al. 2024) and OH/IR stars (Nakagawa et al. in this volume).

5. Future plan

VERA will continue to contribute international collaboration to establish larger VLBI networks. The EAVN activities are currently extending toward the Southeast Asian region, such as the 40 m radio telescope in Thai (see Sugiyama et al. in this volume). Furthermore, VERA is planning to participate in the European VLBI Network (EVN) in the near future. In the past, VERA has joined in the experimental VLBI observations with EVN (Zhao et al. in this volume), as well as the East Asia to Italy Nearly Global VLBI (EATING VLBI) project (Giovannini

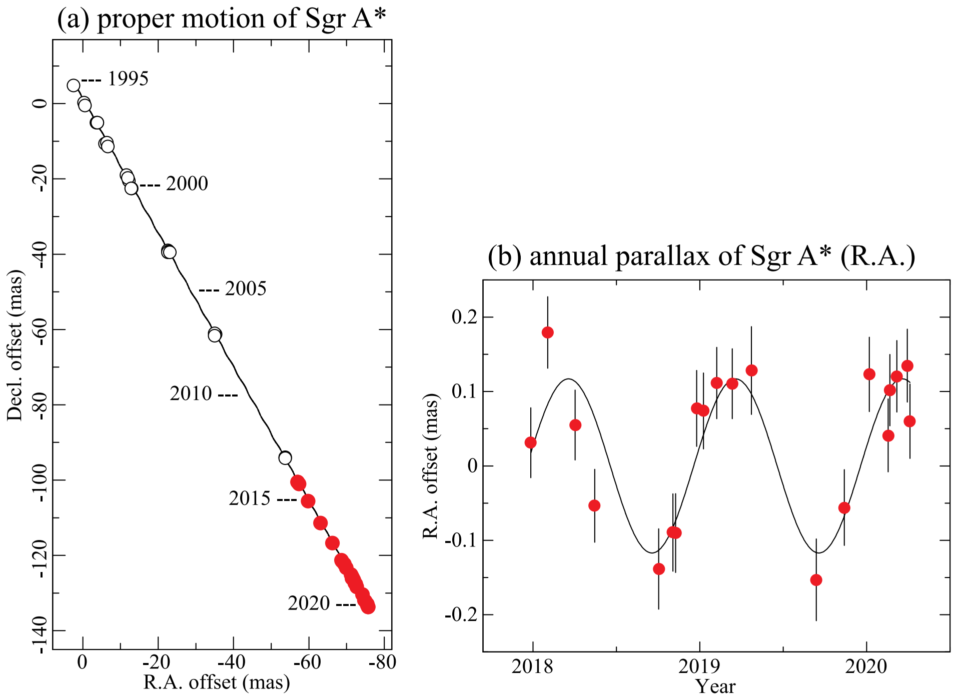

Fig. 3. Results of VERA astrometry of Sgr A* (Oyama et al. 2024). (a) Proper motion measurements on the sky plane. Red filled circles and black open circles represent the data from Oyama et al. 2024 and Reid & Brunthaler (2020), respectively. The solid line shows the modeled motion of Sgr A*, combined both the best-fit proper motion and fixed annual parallax of 0.125 mas.(b) Annual parallax measurements in right ascension (R.A.). The best-fitting proper motion as determined in panel (a) and the constant position offset are removed. The solid line shows the best-fitting parallax of 0.117±0.017 mas, corresponding to a distance of $8.5^{+1.5}_{-1.1}$ kpc.

et al. 2023). Because of the unique locations of the VERA antennas, VERA will provide slightly longer baselines than those between European and KVN stations in the east-west direction (∼1000 km). VERA will be able to play a supplementary role to KVN to add longest baselines in EAVN and hence, improve the angular resolution by ∼10%. The main target for the EVN operation with VERA will be the K-band considering the limitation of VERA at lower frequencies below 22 GHz (i.e. lower sensitivities and single-polarization capabilities). Test observations between VERA and EVN will be conducted soon. In addition, we will also consider a possibility to participate in the Global mm-VLBI Array (GMVA) at 7 mm and 3 mm. For the longer-term plan, VERA will join in the Global VLBI Alliance (GVA) to establish the future world-wide network including SKA-VLBI.

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