Research Interests of Shuangjing Xu (sjxu@kasi.re.kr)

Very long baseline interferometry (VLBI) can achieve microarcsecond accurate (differential) astrometry, which has many unique and key astrophysical applications (Reid and Honma, 2014). Meanwhile, geodetic and (absolute) astrometric VLBI are unique in establishment of the terrestrial reference frame (TRF), the celestial reference frame (CRF), and the earth orientation parameters (EOPs) (Sovers et al., 1998). My research interests cover both fields and include: (1) new techniques/methods to improve VLBI astrometric capability/accuracy, such as, accurate phase calibration, astrometry with multi-frequency/beam, geodetic VLBI at high frequency; and (2) their astrophysical applications, such as, the mass-loss process of evolved stars, Galactic structure, frequency-dependent position difference of quasars and stars (multiple radio bands & Gaia). In addition, I am a crucial member in improving the astrometry performance of the East Asian VLBI Network (EAVN). As follows is individual research:

Work 1: The K-band Geodesy with EAVN (PI)

EAVN is an international collaborative array, which consists of radio telescopes in China, Japan, and Korea. An accurate TRF of EAVN is the foundation for VLBI astrometry. However, many EAVN stations can not join the IVS (the International VLBI Service for Geodesy and Astrometry) observations to determine the station coordinates due to a lack of S/X band (2.3/8.4 GHz).

Instead of IVS sessions, we started conducting the EAVN K-band geodetic observations by collaborating with several IVS stations (Figure 1) since 2019. Based on the K-band geodetic VLBI and the GNSS local tie measurement, a frame offset of KVN and VERA in the ITRF (International Terrestrial Reference Frame) was founded and corrected to 1∼2 cm (Xu et al., 2021). EAVN K-band Geodesy was approved by EAVN directors as a regular project (2 epochs per year, 24 hours per epoch) to improve the EAVN station coordinates to mm level. We will also contribute to the International Celestial Reference Frame (ICRF) at K-band.

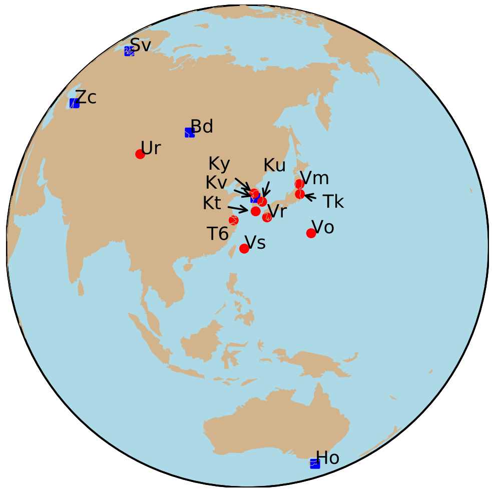

Figure 1: K-band Geodesy with EAVN (red dots) and other IVS (blue squares) stations

I am the PI of this project, and responsible for contacting stations, scheduling, post correlation, and data analysis (all steps, except correlation in SHAO/KASI).

Work 2: The Geodetic VLBI at 22/43/86/129 GHz with KVN (PI)

Geodetic VLBI at S/X band (2.3/8.4 GHz) has made significant contributions to astronomy and geodesy during the past 40 years. In recent years, technical advances in geodetic VLBI are focused on a higher frequency (>20 GHz) and broader observing frequency band (2-14 GHz). The unique 22/43/86/129 GHz receiver of KVN has great potential for geodetic VLBI at high-frequency.

We conducted the first K/Q/W/D band geodetic observation (single band mode) on 2021-12-07. For the first time, we confirmed that the mm-VLBI can be used for the geodetic observations and the weighted RMS is improved due to the reduced source structure and ionospheric effects (Xu et al. in preparation).

Now we are conducting the first broadband geodetic VLBI experiment at high frequency (bandwidth synthesis mode, e.g. Figure 2) using KVN as the pathfinder for the next generation of geodetic VLBI.The sub-picosecond delay measurement is expected with our observations for the first time.

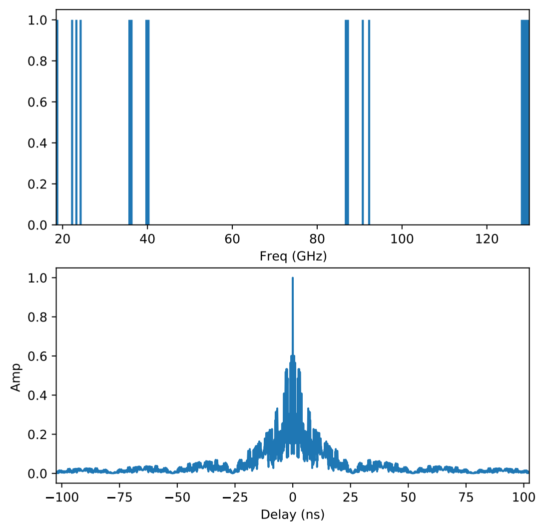

Figure 2: A frequency array and its Delay Resolution Function with KVN

Work 3: The First Astrometric Animation of Water Masers toward an Evolved Star

The EAVN Synthesis of Stellar Maser Animations (ESTEMA) project is a large project aiming at intensive VLBI monitoring H_2O/SiO masers associated with long-period variables (LPVs) over a few stellar pulsation cycles for understanding the microscopic properties of the masers and elucidating the dynamics of the circumstellar envelope (CSE) affected by periodic variation of the stellar luminosity and shock wave propagation induced by stellar pulsation.

We achieved the first result of ESTEMA: the first animation of H_2O masers toward the Mira variable star BX Cam with astrometric steps (Xu et al., 2022b). Data of 37 epochs in total were obtained from 2018 May to 2021 June with a time interval of 3–4 weeks, spanning approximately three stellar pulsation periods, which demonstrated in detail the behaviors of maser emission reflecting the radial acceleration of the maser clumps, periodic variation in regions of maser excitation, and an asymmetrically biased outflow (Figure 3).

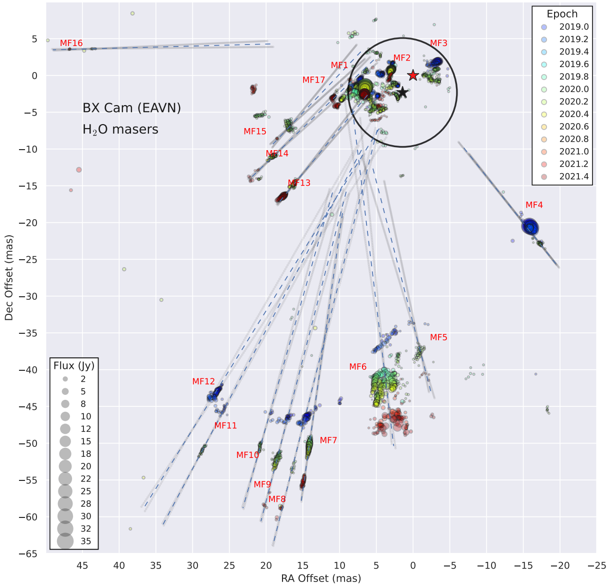

Figure 3: Expansion of the BX Cam flow traced by H_2O masers. Different colors of maser spots indicate different epochs, which are astrometrically fixed with Gaia EDR3. Dashed lines indicate the possible trajectory of masers at a constant velocity.

Astrometry played a key role in registering asymmetrically H_2O masers. We integrated the unique capabilities of EAVN astrometry: the source-frequency phase-referencing (SFPR) astrometry of H_2O and SiO masers (Dodson et al., 2014) with KVN, and the dual-beam phase-referencing astrometry with VERA (Honma et al., 2008). We measured the parallax distance ($\pi = 1.79 \pm 0.08$ mas), the three-dimensional kinematics, which indicates an expanding (13 ± 4 km s^{-1}) CSE, the biased position of the central star between *Gaia* EDR3 and the center position of the ring-like 43 GHz SiO masers.

Work 4: A Milliarcsecond Accurate Position for Sagittarius A*

We found the absolute position of Sgr A*, the compact radio source at the center of the Milky Way, had been uncertain by $\sim$30 mas (Xu et al., 2022a), which will introduce position error for astrometry when using Sgr A* as reference. We reported improved astrometric measurements of the absolute position and proper motion of Sgr A*. Three epochs of phase-referencing observations were conducted with the VLBA for Sgr A* at 22 and 43 GHz in 2019 and 2020. Using extragalactic radio sources with sub-milliarcsecond accurate positions as reference (Figure 4), we determined the absolute position of Sgr A* at a reference epoch 2020.0 to be at α(J2000) $= 17^{\rm h}45^{\rm m}40\overset{\rm s}{.}032863 \pm 0\overset{\rm s}{.}000016$ and δ(J2000) $= -29°00'28\overset{''}{.}24260 \pm 0\overset{''}{.}00047$, with an updated proper motion -3.152 ± 0.011 and -5.586 ± 0.006 mas yr^{-1} in the easterly and northerly directions, respectively.

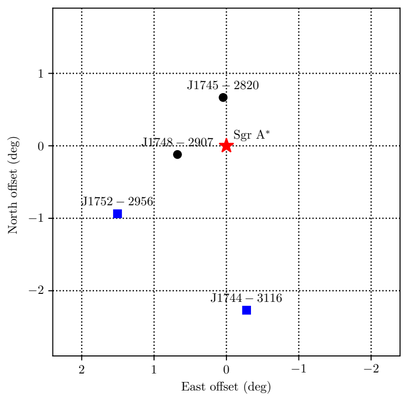

Figure 4: Sgr A* (red star), inaccurate (black dots) and accurate (blue squares) calibrators.

Work 5: Inspect Gaia Results with VLBI Astrometry of Stars

High-accurate astrometry for billions of stars from the Gaia mission promise to revolutionize many areas of stellar astrophysics. However, there are systematic errors exist in Gaia depending on the magnitude, color, and sky position (Lindegren et al., 2021). There is a significant average parallax zero-point of several dozens μas.

Meanwhile, the Gaia Celestial Reference Frame (GCRF) at the bright end (< 13 mag) has a spin offset relative to quasars at the faint end (> 13 mag). An independent assessment of the Gaia astrometric results is required to confirm the Gaia official statement. VLBI astrometry of radio stars should be the most accurate, direct, and reliable method.

We have compared the Gaia DR2 parallaxes of stars with VLBI astrometry to show the systematic errors in Gaia (Xu et al., 2019). The redder AGB stars give larger parallax uncertainties, and one should be cautious when using the Gaia parallaxes for AGB stars (Figure 5). Excluding AGB stars and stars in binary systems, we obtain an average, systematic, parallax offset of -75 ± 29 μas for Gaia DR2. We have several ongoing VLBI projects (with VLBA, EVN, EAVN) for radio star astrometry to link Gaia-CRF and ICRF at the bright end and achieve a better assessment of the Gaia parallax offset.

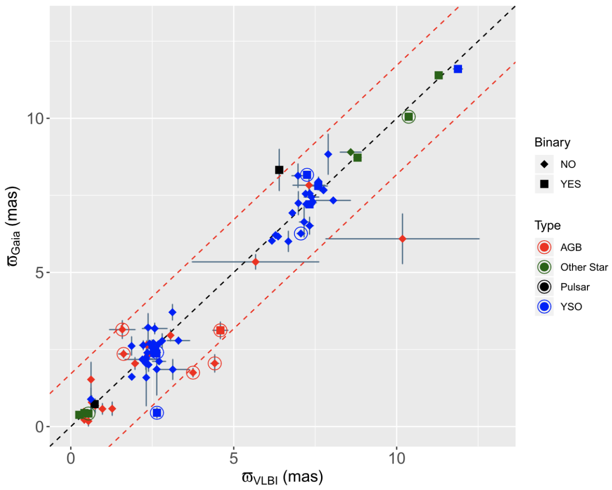

Figure 5: Gaia DR2 vs VLBI parallaxes

Work 6: Methods of Accurate Tropospheric Delay Calibration

VX Sagittarii (VX Sgr) is one of the most massive and luminous red supergiant stars in our Galaxy. However, the parallax distance reported in the Hipparcos catalog for VX Sgr is 0.3 - 0.5 kpc. If Hipparcos is right, VX Sgr would not be classified as a supergiant. We reported a VLBI parallax distance of 1.56 $\pm$ 0.11 kpc using 22 GHz H_2O masers, and solved the distance controversy directly (Xu et al., 2018).

In this data, the uncompensated tropospheric and ionospheric delay dominates the error sources. Although there is geodetic-block or GPS method (Reid and Honma, 2014) to reduce the errors, the uncalibrated delay error (1$\sim$2 cm) limits the quality of the phase-referenced image and the astrometry accuracy. We proposed a two-step method of tropospheric delay calibration, which combines the VLBI geodetic-block or GPS method with a residual tropospheric delay offset calibration using phase-fitting or Image-Optimization method (Xu et al., 2018). The results show that both image quality and astrometry accuracy are improved (Figure 6).

This method might be of benefit when applied to archival VLBI data.

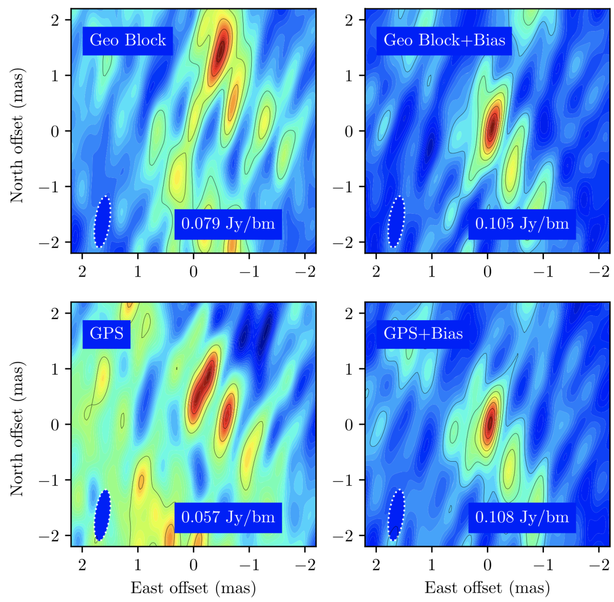

Figure 6: Phase-referenced images, with geodetic-block (upper left), with geodetic-block plus bias correction (upper right), with GPS data (bottom left) and with GPS data plus bias correction (bottom right).

Work 7: Multi-frequency AGN Survey with KVN (MASK) Project

The known VLBI sources at high frequencies (e.g. >22 GHz) are very limited, mainly due to atmospheric fluctuations, which degrade coherence time, and a power-law energy distribution of particles in case of AGNs. However, simultaneous multi-frequency VLBI receiving system of KVN and its powerful VLBI phase calibration technique offer benefits in finding more (weak) sources at millimeter wavelengths.

The MASK project as a KVN legacy program aims to provide the most extensive mm-VLBI catalog at multiple frequencies (22/43/86/129 GHz). We completed the MASK catalog (1533 sources in total) with the detection rate: 1378 sources at 22GHz, 1181 sources at 43GHz, 694 sources at 86GHz, and 356 sources at 129GHz. As a member of the MASK project, I have analyzed $\sim$20% of the data sets with the observing time of $\sim$150 hours, and improved the pipeline for astrometry. Based on the detection results, I proposed the first geodetic VLBI observation at 22/43/86/129 GHz as PI (see Work 2).

Work 8: The Galactic Astrometry with EAVN

I am a key member of EAVN astrometry working group to improve the astrometry performance and scientific production of EAVN.

"Astrometric Performance Evaluation of EAVN" project (co-PI). We conducted several test astrometric observations, (such as, the parallax of W3OH, QSO pair observations), with EAVN to evaluate the astrometry performance. We confirmed that relative astrometric observation with EAVN can achieve positional accuracies of $\sim$20 μas [1].

Galactic astrometric projects (PI/co-I). We are using EAVN for astrometric observations toward the Extreme Outer Galaxy, radio star, and X-ray binary. Several papers are in preparation.

References

[1] R. Dodson et al., **148**, 97, 97 (2014).[2] M. Honma et al., **60**, 935–950 (2008).[3] L. Lindegren et al., **649**, A2, A2 (2021).[4] M. J. Reid et al., **52**, 339–372 (2014).[5] O. J. Sovers et al., Reviews of Modern Physics **70**, 1393–1454 (1998).[6] S. Xu et al., **875**, 114, 114 (2019).[7] S. Xu et al., in 25th european vlbi group for geodesy and astrometry working meeting, Vol. 25, edited by R. Haas (Dec. 2021), pp. 71–73.[8] S. Xu et al., **859**, 14, 14 (2018).[9] S. Xu et al., arXiv e-prints, arXiv:2210.03390, arXiv:2210.03390 (2022).[10] S. Xu et al., arXiv e-prints, arXiv:2210.02812, arXiv:2210.02812 (2022).

[1] `https://radio.kasi.re.kr/status_report/files/Status_Report_EAVN_2023A.pdf`