PROCEEDINGS OF SCIENCE

# Ultra-wide band polarimetry using VLBI Exploration of Radio Astrometry (VERA)

**Yoshikai Hagiwara,**[a,e,*] **Kazuhiro Hada,**[b,c] **Mieko Takamura,**[b,d] **Tomoaki Oyama**[b] **and Syunsaku Suzuki**[b]

[a] *Natural Science Laboratory, Toyo University, 5-28-20 Hakusan Bunkyo-ku Tokyo 112-8606, Japan; yhagiwara@toyo.jp*

[b] *Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, 2-12 Hoshigaoka, Mizusawa, Oshu, Iwate 023-0861, Japan*

[c] *Astronomical Science Program, The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*

[d] *Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1, Hongo, Tokyo 113-0033, Japan*

[e] *ASTRON and Joint Institute VLBI for ERIC (JIVE), Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, the Netherlands*

*E-mail:* yhagiwara@toyo.jp

We report on recently conducted technical developments of front- and back-end for four 20-m radio telescopes of VLBI Exploration of Radio Astrometry (VERA). In this short article, a brief overview of the developments of a dual circular polarization receivers and ultra-wide band (16 Giga bit $s^{-1}$ ) recording systems that were installed to each of the four telescopes of VERA is presented. With the new technical developments that enable wider band VLBI polarization observations at 22 and 43 GHz bands, it is expected that VERA will reveal magnetic fields in plasma jets of active galactic nuclei, masers in star-forming cites, and late-type stars at unprecedented sensitivity. The wide band calibrated spectra, delay solutions, and the polarization intensity maps of extragalactic sources at 22 and 43 GHz that obtained from the most recent test observations are presented to show the current capabilities of the VERA polarimetry performance.

*15th European VLBI Network Mini-Symposium and Users' Meeting (EVN2022)*
*11-15 July 2022*
*University College Cork, Ireland*

[1] Current address: Toyo University, 5-28-20 Hakusan Bunkyo-ku Tokyo 112-8606, Japan
[*] Speaker





PoS(EVN2022)052

## 1. Overviews of front-end of VERA

VLBI (Very Long Baseline **Interferometry**) Exploration of Radio Astrometry (VERA) is consisting of four identical 20-m telescopes, located throughout Japan from Honsyu to Ishigaki-jima island in Okinawa on baselines up to 2300 km. VERA is operated by NAOJ Mizusawa VLBI observatory. Each of the 20-m telescopes is equipped with the dual-beam receiving system dedicated for phase-referencing astrometry [1, 2]. As shown in Figure 1, VERA received signals at 22 and 43 GHz only in left-hand circular polarization (LHCP) with the dual-beam receiver (A- and B-beam) until around 2018. New 22 and 43 GHz receivers with dual circular polarization by adding a right-hand circular polarization (RHCP) receiver to the A-beam receiving system have been installed to all the four 20-m telescopes, which enabled the simultaneous **reception in both LHCP and RHCP**. **It should be remarked that dual polarization and dual band observations at 22 and 43 GHz cannot be performed at the same time with the current front-end system**.

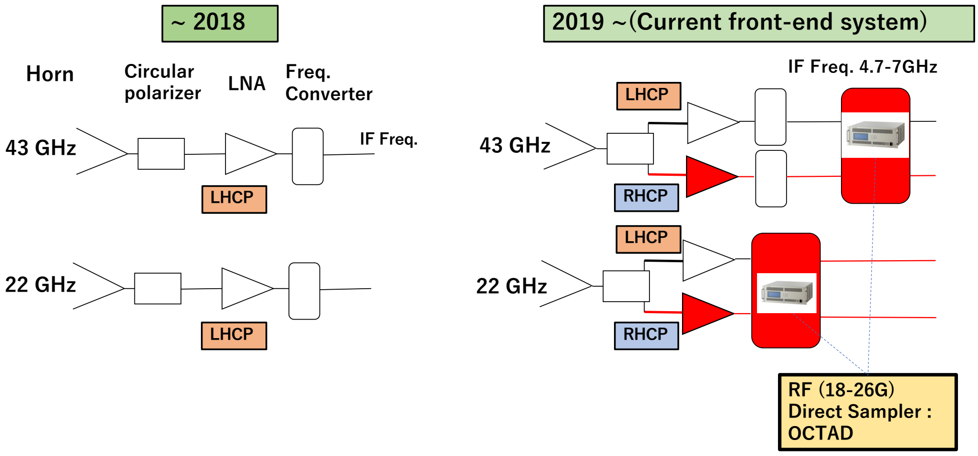


**Figure 1:** A schematic overview of the old (~2018) and current (2019~) systems of VERA front-end. Instruments in the area colored in red **(RHCP receivers and OCTAD; radio-frequency signal analog-to-digital sampler)** were installed only to the A-beam receiver system at the four telescopes of VERA.

## 2. Test observations and data analysis

In order to test performances of VERA wide-band polarimetry, commissioning observations were conducted for 19 hours at 22 GHz on 2022 March 9 and at 43 GHz on March 21. The summary of the observations is listed in Table 1. These observations were performed as part of a wide-band polarimetry science program using VERA. In these observations, we observed bright quasars and masers as calibrators to evaluate the polarization performance. The calibrator sources included to the observations are **0235+164, 0528+134, 3C 273, 3C 454.3, 3C 84, OJ 287, W3OH, and Orion-KL**. Here we focus on the analysis of the calibrators to demonstrate the polarimetric VLBI performance of VERA. The scientific results on the science targets are discussed in a separate article [4]. Both of 22 and 43 GHz sessions were performed at a recording rate of 16 Giga bit $s^{-1}$ in which radio signals were received in four 512 MHz sub-bands in dual circular polarizations, resulting to a total bandwidth of 2048 MHz per polarization.

**Table 1:** Summary of test polarization observations using VERA.

| | | |
|---|---|---|
| Frequency (GHz) | 22 | 43 |
| Date | 2022-3-9 | 2022-3-21 |
| System temperatures (K) | | |
| Mizusawa, Iriki stations | 100-200 | 200-1000 |
| Ogasawara, Ishigaki stations | 150-400 | 200-1000 |
| The number of a sub-band | 4 | 4 |
| IF sub-bandwidth (MHz) | 512 | 512 |
| Total bandwidth (MHz) | 2048 | 2048 |
| The number of circular polarizations | 2 | 2 |
| Recording rates (Gigabit sec$^{-1}$) | 16 | 16 |
| Correlation | Softcos (FX-type) | Softcos (FX-type) |

Most of the sources were observed over a wide range of parallactic angles, which was important to perform reliable calibration of polarization leakage terms (D-terms). Correlation of the VLBI data was executed using the FX-type Software Correlator (softcos or OCTACOR2) at NAOJ Mizusawa VLBI Observatory [3]. Details of the observations are summarized in Table 1.

The calibration of data was performed with the Astronomical Image Processing System (AIPS) developed at the National Radio Astronomy Observatory (NRAO) [5]. The data analysis procedure was performed in the same manner with other VLBI facilities such as the Very Long Baseline Array (VLBA). D-terms were solved for each sub-band separately by using the AIPS task LPCAL.

## 3. Results

Figure 2 displays plots of the 22 GHz calibrated spectra of 3C84 on the Mizusawa to Iriki baseline with four polarizations RR, LL, RL, and LR. The plots show that the observations were conducted with four IFs, with a 512 MHz bandwidth each. Figures 3 show signal-to-noise ratio (SNR) of delay solutions of 3C84 with 1 and 16 Giga bit s$^{-1}$ at 22 (upper) and 43 GHz (lower) using AIPS FRING [5]. As a result of changing the recording rate from 1 to 16 Giga bit s$^{-1}$ , it is clear that the SNRs have been dramatically improved both at 22 and 43 GHz. Figures 4 show color linear-polarization ($P = \sqrt{Q^2 + U^2}$) intensity maps obtained for OJ287 and 1H 0323+342, which are overlaid on total-intensity (Stokes I) contour maps. In these maps, polarization emission is detected at SNR>5. We do not present Electric Vector Position Angle (EVPA) distributions as the absolute EVPA information is required from other telescopes, however, which needs to be implemented to our further analysis. **The EVPA determination was not applied to our observations, however we plan to correct it using KVN (Korean VLBI Network) and KaVA (KVN and VERA Array) in future observations.**

## 4. Performance evaluation

One of our aims of the test observations was to estimate D-term amplitudes for each VERA telescope at 22 GHz and 43 GHz to evaluate the performance required for polarization observation.



PoS(EVN2022)052

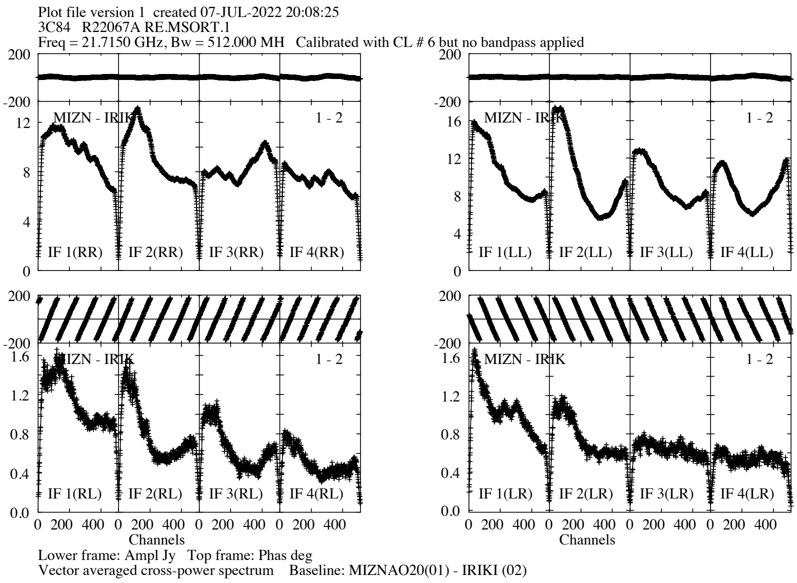


**Figure 2: Fringe plots of the 22 GHz spectra of 3C84 with the four polarizations on the Mizusawa to Iriki baseline, obtained from the AIPS POSSM. These plots show that the observations were conducted with four IF sub-bands, each of which has a 512 MHz bandwidth per polarization. Large delays are seen in the R-L and L-R delay plots (lower), which were corrected before running the AIPS LPCAL.**

In Table 2, the D-terms at 22 and 43 GHz obtained for each telescope and polarization are summarized [7]. The D-terms at 22 GHz derived from different calibrators were in good agreement with each other at all the four stations. The D-term amplitudes range 4–7% over the four stations with a standard deviation of within 2%, whereas at 43 GHz, the amplitudes are estimated larger than those at 22 GHz. However, they look largely constrained to be within ~10%. We note that the D-term solutions seem to show some slight difference between the IF sub-bands, which could depend on frequency dependence of D-term due to the wide receiving bandwidth of 2048 MHz of our observations. This ought to be checked by further test observations. For example, the D-term of the Ishigaki station is 14.3 ± 2.2 %, relatively large.

Compared with D-term amplitudes (< ~5%) obtained from NRAO Very Long Baseline Array (VLBA) [6], the D-terms of VERA are larger. It is not also certain that this is due to better calibration accuracy as a result of the larger number of VLBA baselines, or more intrinsic due to difference of the antenna feeds. The D-terms of the KVN (Korean VLBI Network) are ~3.5–11% at 22 GHz and ~4.5–6.5% at 43 GHz [8], closer to those of VERA. **However, the larger D-term amplitudes could be due to the fact that the D-terms vary within the large fractional bandwidth, which will be clarified in further analysis.**

Overall, the D-terms estimated from the first ultra-wide band polarimetric test observations are very encouraging without any serious issues that we could produce linear polarization maps with VERA, as shown in Figures 4 at both 22 and 43 GHz. OJ 287 has been regularly monitored with VLBA at 15 GHz through the MOJAVE or the Boston University blazar program [9] and at 43 GHz [10]. The polarization image of the galaxy obtained with VERA is consistent overall with those typically measured from the VLBA observations, confirming the capability of VERA

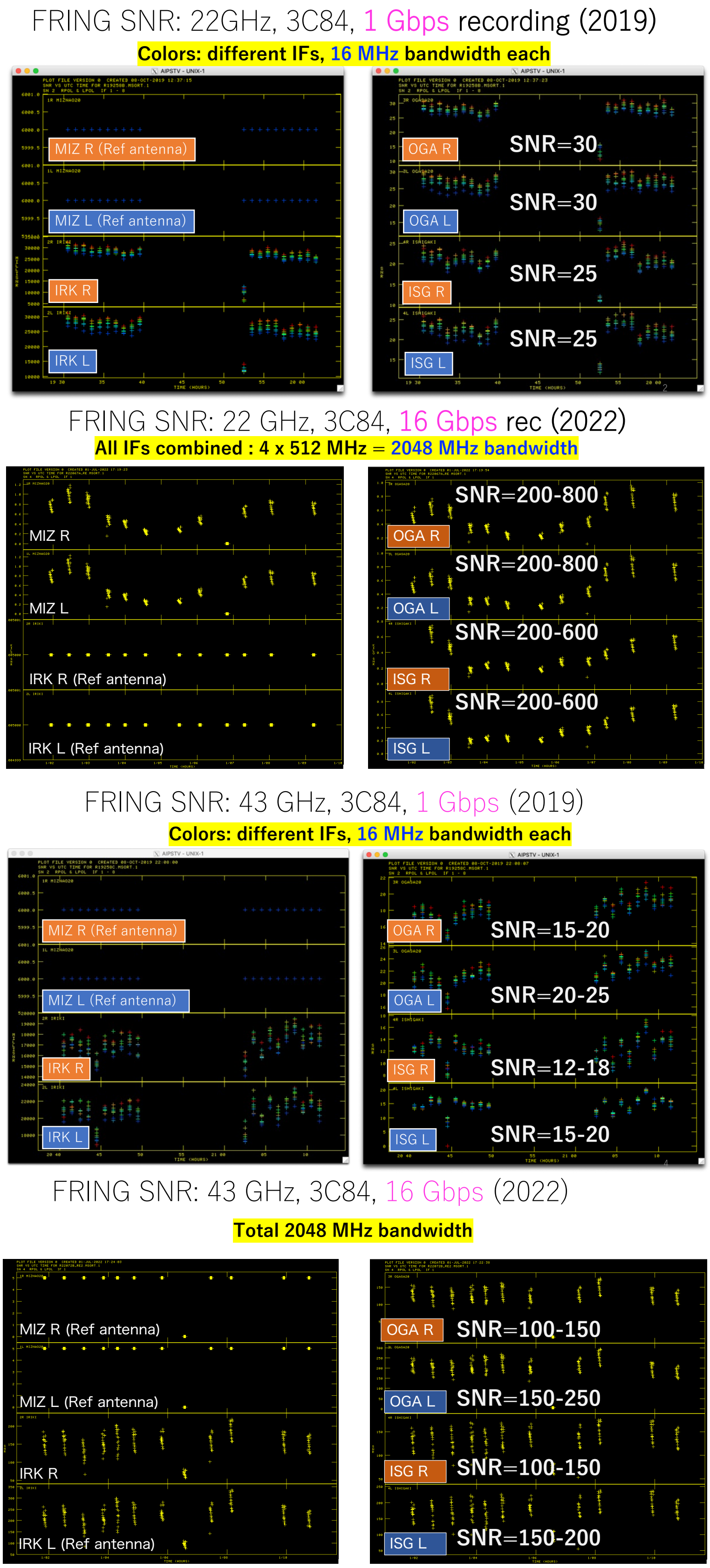


**Figure 3:** SNR plots of delay solutions of 3C 84 with 1 and 16 Giga bit $s^{-1}$ at 22 (upper) and 43 GHz (lower). At the both frequencies, the SNRs are improved changing the recording rate from 1 to 16 Giga bit $s^{-1}$ .

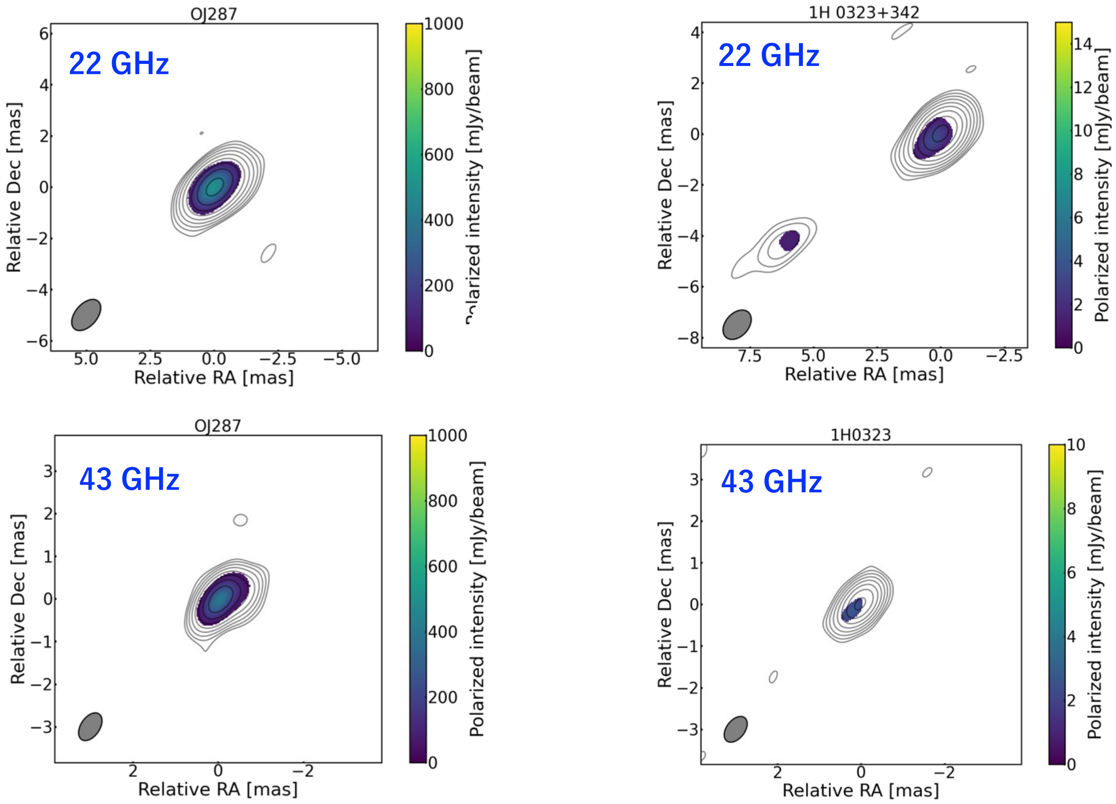


**Figure 4: Linear polarization maps of 3C84 and 1H 0323+342 obtained from the dual-polarization observations using VERA. The EVPA calibrations are not applied to these maps. In each panel, contour levels of total intensity (I) increase with powers of two, starting from the 3 $\sigma$ levels. (1 $\sigma$ levels are 6.1 mJy beam$^{-1}$ at 22 GHz and 5.0 mJy beam$^{-1}$ at 43 GHz for OJ 287 and 0.14 mJy beam$^{-1}$ at 22 GHz and 0.28 mJy beam$^{-1}$ at 43 GHz for 1H 0323+342 [4]. The synthesized beams are plotted at the left bottom of each panel.**

for polarimetric study. **Given the polarization image of the narrow-line Seyfert 1 galaxy 1H 0323+342, the obtained rotation measure of the galaxy is discussed more in detail in [4].** The detection of large rotation measure of the galaxy was first realized by the combination of the new dual-polarization and ultra-wide band capabilities of VERA.

More details of performance verification of the polarimetric VLBI capabilities of VERA are described in [4, 7].

**Table 2:** D-terms of the VERA 20-m telescopes

| Telescope | 22 GHz RCP | 22 GHz LCP | 43 GHz RCP | 43 GHz LCP |
|---|---|---|---|---|
| Mizusawa (MIZ) | 6.3 ± 2.0 | 6.2 ± 1.7 | 7.7 ± 1.2 | 9.0 ± 2.0 |
| Iriki (IRK) | 7.1 ± 1.3 | 7.0 ± 1.3 | 5.7 ± 1.3 | 5.3 ± 1.3 |
| Ogasawara (OGA) | 5.7 ± 1.0 | 5.5 ± 1.3 | 11.6 ± 1.2 | 10.9 ± 1.2 |
| Ishigak-Jima (ISG) | 4.0 ± 1.9 | 4.6 ± 1.9 | 11.1 ± 3.0 | 14.3 ± 2.2 |

## 5. Future prospects

It is expected that more observing capabilities will be implemented to VERA telescopes in future, such as 22 and 43 GHz simultaneous observations with dual-polarizations at 16 Giga bit $s^{-1}$ and "super" ultra-wide band observation at 32 Giga bit $s^{-1}$ .**We recognize that for such further broadband observations, we need to tackle with the issues of, for example, calibration of larger D-term amplitudes and absolute EVPA calibration across the entire broadband.** With the new polarimetric VERA capability, very recently east-Asian VLBI Network (EAVN) and East Asia to Italy Nearly Global VLBI (EATING VLBI) have started projects on polarization observations [e.g. 11], which will enable imaging of magnetic fields in active galactic nuclei(AGN) and Faraday rotation measurement towards AGN at 22 and 43 GHz with better u-v coverage and sensitivity, compared with VERA.

## Acknowledgments

We gratefully acknowledge the support of the Mizusawa VLBI Observatory staff for their assistance with observations. YH thanks Noriyuki Kawaguchi for his useful advice on the development. We also thank the anonymous referee for suggestions and valuable comments to improve this article. The VERA is operated by National Astronomical Observatory of Japan. This research was funded by JSPS KAKENHI grant number JP15H03644(Y.H.) and JP19H01943(K.H.). Part of the research was supported by the Inoue Enryo Memorial Grant, TOYO University in Japan. VERA is operated by National Astronomical Observatory of Japan. YH is grateful to ASTRON and JIVE for allowing him to stay in Dwingeloo for research.

## References

[1] Honma, M.; Kawaguchi, N.; Sasao, T. Science with VERA: VLBI exploration of radio astrometry. In Proceedings of the SPIE, Radio Telescopes. Munich, Germany, 27-31 March **2010**, 4015, 624–631.

[2] Kawaguchi, N.; Sasao, T.; Manabe, S. Dual-beam VLBI techniques for precision astrometry of the VERA project. In Proceedings of the SPIE, Radio Telescopes. Munich, Germany, 27-31 March **2010**, 4015, 544–551.

[3] Oyama, T.; Kono, Y.; Suzuki, S.; et al. New VLBI Observing System 'OCTAVE-Family' to Support VDIF Specifications with 10 GigE for VERA, JVN, and Japanese e-VLBI (OCTAVE). In Seventh General Meeting (GM2012) of the international VLBI Service for Geodesy and Astrometry (IVS). Madrid, Spain, 4-9 March **2012**, 91–95.

[4] Takamura, M.; Hada, K.; Honma, M.; Oyama, T.; Yamauchi, A.; Suzuki, S.; Hagiwara, Y.; et al. Probing the Heart of Active Narrow-line Seyfert 1 Galaxies with VERA Wideband Polarimetry. **2023**, arXiv, arXiv:2306.03139.

[5] Greisen, E.W. The Astronomical Image Processing System. In Acquisition, Processing and Archiving of Astronomical Images. **1990**, 125–142.

[6] Gómez, J. L.; Marscher, A.P; Alberdi, A.; Jorstad, S.G.; Agudo, I. Polarization calibration of the VLBA using the D-terms. VLBA Scientific Memo. **2002**, 30, 1-16

[7] Hagiwara, Y.; Hada, K.; Takamura, M.; Oyama, T.; Yamauchi A.; Suzuki, S. Demonstration of Ultrawideband Polarimetry Using VLBI Exploration of Radio Astrometry (VERA). **2022**, Galaxies, 10, 114.

[8] Park, J.; Kam, M.; Trippe, S.; Kang, S.; Byun, D.-Y.; Kim, D.-W.; Algaba, J.-C.; et al. Revealing the Nature of Blazar Radio Cores through Multifrequency Polarization Observations with the Korean VLBI Network. **2018**, *Astrophys. J.*, 860, 112 (21pp).

[9] Lister, M.L.; Aller, M.F.; Aller, H.D.; Hodge, M.A.; Homan, D.C.; et al. MOJAVE. XV. VLBA 15 GHz Total Intensity and Polarization Maps of 437 Parsec-scale AGN Jets from 1996 to 2017. **2018**, *Astrophys. J. Suppl. Ser.*, 234, 12 (6pp).

[10] Jorstad, S.G.; Marscher, A.P.; Morozova, D.A.; Troitsky, I.S.; Agudo, I.; Casadio, C.; et al., Kinematics of Parsec-scale Jets of Gamma-Ray Blazars at 43 GHz within the VLBA-BU-BLAZAR Program. **2017**, *Astrophys. J.*, 846, 98 (35pp).

[11] Giovannini, G.; Cui, Y.; Hada, K.; Yi, K.; Ro, H.; Sohn B. W.; Takamura, M.; et al. The Past and Future of East Asia to Italy: Nearly Global VLBI. **2023**, Galaxies, 11, 49.

PoS(EVN2022)052