Geodesy, Astrometry and High-resolution Imaging at K band with the European VLBI Network

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Abstract The European VLBI Network (EVN) has been used for geodetic observations at K band within the context of the EC-funded project JUMPING JIVE. While the primary motivation of the observations was to determine the geodetic positions of the non-geodetic EVN radio telescopes (i.e., ones not equipped with dual-frequency S/X receivers), the data prove also to be of high interest for astrometry and imaging. Based on the data collected, positions of four non-geodetic EVN telescopes have been determined with cm-level precision. Further to the geodetic results, high-resolution K band images of 80 defining sources from the third realization of the International Celestial Reference Frame (ICRF3) have been obtained. A specificity of the EVN images is that they show increased resolution compared to those derived from the Very Long Baseline Array. Additionally, comparable resolution is usually obtained along right ascension and declination, which is very valuable, especially for sources at low declinations. With its long baselines (from Europe to Asia and from Europe to South Africa), the EVN can help strengthen the K band celestial reference frame, one of the three components of the ICRF3, and contribute to the realization of the next ICRF.

Keywords VLBI, EVN, geodesy, astrometry, ICRF, imaging

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1 Introduction

The work reported in this paper was initiated in the context of the JUMPING JIVE project[1], an EC funded project for the period 2016–2021 whose objective was to enhance the profile of the Joint Institute for VLBI ERIC (JIVE). In this project, Work Package 6 "geodetic capabilities" was aimed at implementing an operational geodetic path at the European VLBI Network (EVN) software correlator (SFXC) at JIVE and measuring the geodetic position of the non-geodetic EVN telescopes [1]. For the latter, two experiments have been carried out with the EVN at K band in June 2018 and October 2020 [2]. Another such experiment was conducted after the project was terminated, in June 2023, to supplement the initial data set. The sources targeted were part of the third realization of the International Celestial Reference Frame (ICRF3) [3], including many of the defining sources. Besides determining the telescope positions, the observations had also two secondary goals: (i) assessing the potential of the EVN for global astrometry at K band and (ii) imaging the sources at high resolution.

Section 2 describes the observations and their post-processing, while Sections 3, 4, and 5 report geodetic, astrometric, and imaging results from the analysis of part of the data. Section 3 provides geodetic positions for four non-geodetic EVN telescopes based on the observations of EC065. In Section 4, the same data set is used to assess the potential of the EVN for global astrometry. Section 5 presents results of imaging from the observations of EC076, including statistics on the image dynamic range and restoring beam size. Section 6 summarizes the results and draws future prospects.

[1] See the web page of the project at https://jumping.jive.eu/.

2 Observations

The observations collected for the purpose of the project were acquired during two 24-hour EVN experiments that took place on 13 June 2018 (EC065) and 23 October 2020 (EC076) and one 48-hour experiment conducted on 3 and 4 June 2023 (EC092). The VLBI network for these experiments consisted of all EVN radio telescopes that have the capability of observing at K band, namely 18 telescopes in Europe, Asia, and South Africa, provided these telescopes were available at the time of the experiments. The network was further augmented with the four e-MERLIN out-stations with K band capability (Cambridge, Darnall, Knockin, and Pickmere in the UK) and the 26-m antenna in Hobart (Australia). The latter was arranged only for EC076 and EC092. In all, this forms a large network of 23 telescopes (see their locations in Figure 1). Because of the unavailability of some antennas at some epochs or issues with correlation or fringe fitting, the actual data sets available for analysis had fewer stations, namely 14 stations for EC065 and 20 stations for EC076. The data of EC092 are in the final stage of processing.

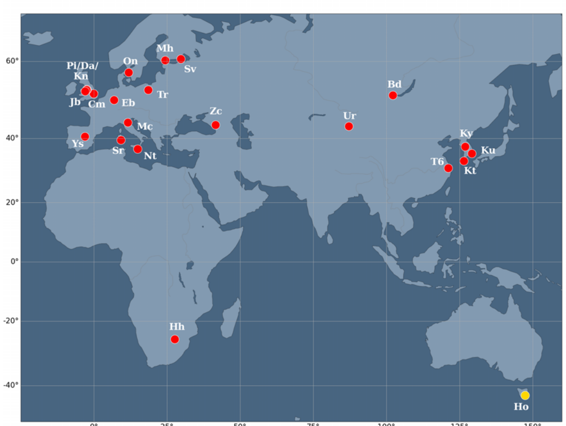

Fig. 1 Geographical location of the 23 VLBI telescopes involved in the observations. Red dots denote EVN and e-MERLIN telescopes. The yellow dot denotes a non-EVN telescope (Hobart).

In total, 279 sources from the ICRF3 were observed in one or the other of the experiments. Most of the sources (239 sources) were chosen among the ICRF3 defining sources to properly tie the celestial reference frame to the ICRF3, limit potential source structure effects, and allow for a high-resolution imaging survey at K band of virtually all ICRF3 defining sources north of $-40°$ declination. In particular, all sources observed in EC076 and EC092 were exclusively ICRF3 defining sources.

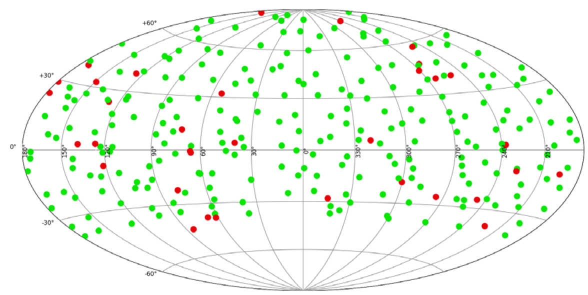

Fig. 2 Sky distribution of the 279 sources observed during our three K band EVN experiments. Green dots indicate ICRF3 defining sources, while red dots indicate non-defining sources.

The scheduling of the observations was achieved using NASA's SKED software. While the sky coverage above each antenna was optimized in the usual way to allow for the estimation of tropospheric parameters for geodesy, we also arranged for the observations in each experiment to be reasonably spread over all sources and forced each scan to include a minimum of four telescopes so that all scans are useful for imaging.

The data were processed with the SFXC correlator and post-processed in two ways: (i) through the newly-implemented geodetic path at the SFXC correlator [4] for geodesy and astrometry and (ii) in the standard way with AIPS by using the calibration information (gain curves and system temperatures) attached to the experiments for imaging. Geodetic and astrometric analysis from EC065 along with imaging results from EC076 are presented in the following sections.

3 Geodetic Positions of EVN Telescopes

The analysis of the data from EC065 for geodesy was accomplished with the Vienna VLBI software [5] following standard astronomical and geophysical modeling and by using total electron content maps from the International GNSS Service to correct the observed VLBI delays for the contribution of the ionosphere. Positions of sources were fixed to the K band component of ICRF3, while Earth Orientation Parameters were taken from the IERS (C04_20 solution). All station positions were estimated subject to No Net Translation (NNT) and No Net Rotation (NNR) constraints relative to the ITRF2020 [6]. Based on this analysis, positions at the centimeter level have been estimated for the four non-geodetic EVN telescopes listed in Table 1.

Table 1 ITRF2020 geodetic positions of four EVN telescopes.

Telescope	X (m)	Y (m)	Z (m)
JODRELL2	3822846.494	−153801.917	5086286.157
(Jb)	±0.008	±0.002	±0.011
SARDINIA	4865183.222	791922.560	4035136.165
(Sr)	±0.011	±0.004	±0.010
TORUN	3638558.157	1221970.075	5077036.948
(Tr)	±0.004	±0.002	±0.004
KVN YONSEI	−3042281.090	4045902.606	3867374.276
(Ky)	±0.009	±0.012	±0.013

Notes. Coordinates are for the epoch of EC065, i.e., 2018.45. JODRELL2 is the Mk2 telescope in Jodrell Bank (UK).

Further to this determination, an additional step was taken by incorporating into the analysis archived K band EVN data (also of geodetic type) that involved the Jodrell Bank telescope and making a global solution to measure its velocity. As shown in Figure 3, this leads to motions of 1–2 cm/yr for the individual coordinates, in agreement with the magnitude of the motions derived from plate motion models for Europe.

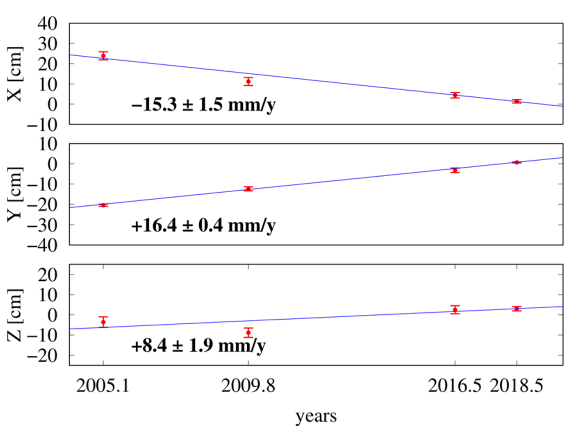

Fig. 3 Velocity of the Mk2 telescope in Jodrell Bank, as estimated from a global analysis including the data of EC065 plus archived geodetic EVN observations at K band.

4 Potential of the EVN for Astrometry

Based on the EC065 data, an astrometric solution was also produced. The setup was similar to that of the geodetic analysis reported in Section 3 with the exception that source positions were estimated (subject to an NNR constraint relative to the ICRF3). The goal of this solution was not to compare in detail with the ICRF3 positions but rather to determine the precision of the source coordinates derived from such observations. As shown in Figure 4, source coordinate uncertainties have a floor of about 0.2 mas, a level that demonstrates the capability of the EVN to achieve precise global astrometry at K band and therefore the potential of the network to strengthen the ICRF at this frequency band. While declination errors increase towards lower declinations (as is usually the case in global astrometry observations), we expect the situation to improve in the two subsequent experiments (EC076 and EC092) thanks to the participation of the Hobart telescope, which adds long North-South baselines between Asia and Australia.

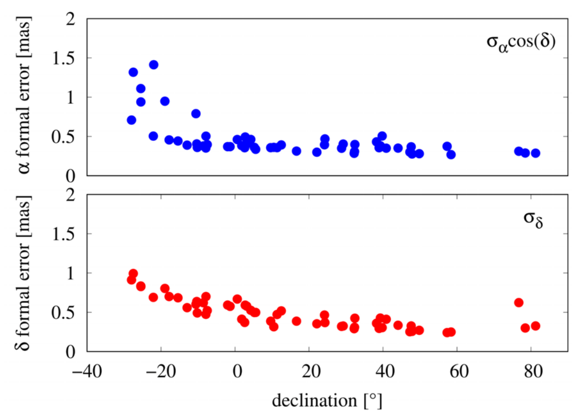

Fig. 4 Right ascension and declination errors as a function of declination as derived from the data of EVN experiment EC065. Three sources with coordinate errors above 2 mas are not shown.

5 Imaging ICRF Sources

The imaging of the EC076 data was accomplished using DIFMAP in a fully-automatic mode after averaging the visibilities over 10-second periods of time. Based on this procedure, all of the 80 sources observed in

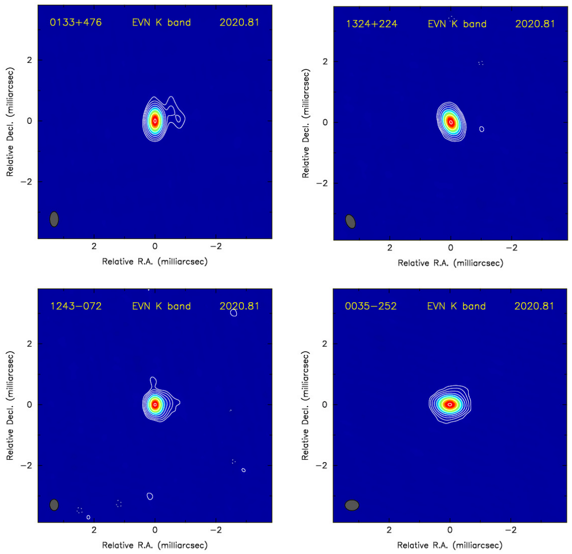

Fig. 5 VLBI images at K band of four ICRF3 defining sources (0133+476, 1324+224, 1243−072, 0035−252) from the data of EVN experiment EC076. Contour levels are drawn at ± 0.75, 1.5, 3, 6, 12, 24, 48 and 96% of the image peak brightness.

EC076 have been successfully imaged, demonstrating the potential of the EVN for such work. The image dynamic range (defined as the ratio of the peak brightness to the rms of the brightness in the residual map) is up to 1,300, with a median value of 490. Figure 5 shows a sample of the derived images for four sources at different declinations (48°, 22°, −7°, and −25°). Interestingly, only moderately elongated restoring beams are obtained for sources at low declinations (see the distribution of the beam axis ratio in Figure 6), an unusual but favorable situation which results from the network including long North-South baselines between Hartebeesthoek and Europe and between Hobart and Asia.

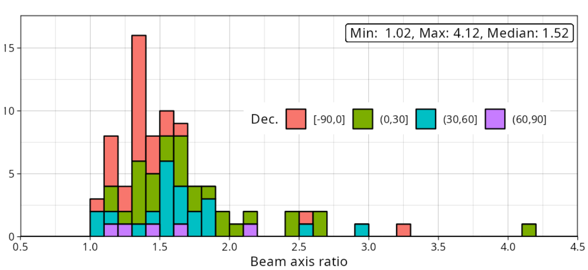

Fig. 6 Distribution of the beam axis ratio for the 80 sources imaged from the data of EVN experiment EC076. The sources are split into four declination ranges and color-coded accordingly.

Apart from a few exceptions, the sources are found to be mostly very compact at the EVN resolution, which confirms that they qualify well as defining sources for the ICRF. Figure 7 compares our EVN image of a source that is not point-like (1418+546) with a previously published Very Long Baseline Array (VLBA) image of the same source, also at K band [7]. Though not at the same epoch, the EVN and VLBA images compare well, indicating a similar jet-like structure elongated in the same direction. The comparison of the two images also shows that the EVN provides somewhat higher resolution with respect to the VLBA. Considering our entire set of 80 images, the minor axis of the restoring beam ranges from 0.15 mas to 0.43 mas, with a median value of 0.28 mas. In comparison, the maximum resolution that the VLBA can reach is about 0.3 mas. Such increased resolution should help probing source structure even closer to the core, which would be of interest for the K band celestial reference frame but also for understanding the physics of the underlying extragalactic sources.

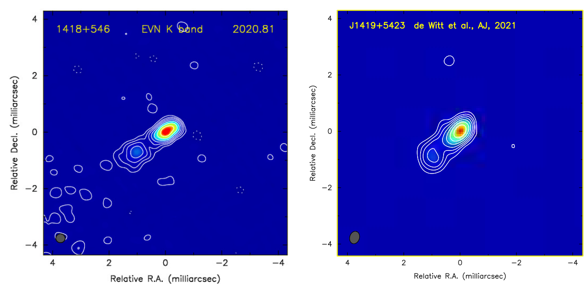

Fig. 7 Comparison of EVN (left) and VLBA (right) images of the source 1418+546 (J1419+5423). The VLBA image [7] is for epoch 2017.02. Contour levels are drawn at ± 0.64, 1.70, 3.41, 6.82, 13.63, 27.26, and 54.53% of the image peak brightness.

6 Conclusions

Based on K band EVN data, geodetic positions of four non-geodetic EVN telescopes have been determined with cm precision in the ITRF2020 terrestrial reference frame. Together with archived EVN data, this determination has also allowed for the estimation of the velocity of the Jodrell Bank Mk2 telescope to about 2 mm/yr. A test astrometric analysis estimating source positions from the same data set shows a floor of about

0.2 mas in the source coordinate uncertainties, hence demonstrating the potential of the EVN for global astrometry at this frequency band. Additionally, high-resolution images of 80 ICRF3 defining sources have been produced. Besides their higher angular resolution, a specific feature of these images is that they often show comparable resolution in the East-West and North-South directions owing to the presence of long EVN baselines in the two directions. This result highlights the high relevance of the EVN for imaging the ICRF sources at K band aside from the aforementioned geodetic and astrometric applications. Future plans include completing the geodetic, astrometric, and imaging analysis of all EVN data collected so far and pursuing further the observations, either as EVN-only or global EVN+VLBA experiments, in the light of the preparation of the next realization of the ICRF [8].

Acknowledgements

The European VLBI Network (EVN) is a joint facility of independent European, African, Asian, and North American radio astronomy institutes. The results presented in this paper were derived from EVN data with project codes EC065 and EC076. We are grateful to the Hobart team at the University of Tasmania for having their 26-m antenna joining the EVN for part of the observations, which strengthened significantly the geometry of the network. PC and AC acknowledge support from the "Observatoire Aquitain des Sciences de l'Univers" (OASU). This research received funding from the European Union's Horizon 2020 Research and Innovation Programme, under grant agreement No. 730884. We also thank RadioNet for its support.

References

1. F. Colomer, M. Kettenis, R. M. Campbell, P. Charlot, A. Szomoru (2019) Geodetic capabilities of the JIVE SFXC correlator. In Proceedings of the 10th IVS General Meeting, Eds. K. L. Amstrong, K. D. Baver, and D. Behrend, NASA/CP-2019-219039, p. 117–120.
2. M. E. Gómez, P. Charlot, R. M. Campbell, M. Kettenis, A. Keimpema (2021) Towards the determination of the geodetic position of non-geodetic EVN antennas. In Proceedings of the 25th European VLBI Group for Geodesy and Astrometry Working Meeting, Ed. R. Haas, p. 39–42.
3. P. Charlot, C. S. Jacobs, D. Gordon, S. Lambert, A. de Witt, et al. (2020) The third realization of the International Celestial Reference Frame by very long baseline interferometry. *Astronomy & Astrophysics*, 644, A159.
4. M. E. Gómez, M. Kettenis, P. Charlot, R. M. Campbell, A. Keimpema (2019) Implementation of a Geodetic Path at the JIVE Correlator. In Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, Eds. R. Haas, S. Garcia-Espada, and J. A. López Fernández, p. 112–115.
5. J. Böhm, S. Böhm, J. Boisits, A. Girdiuk, J. Gruber, et al. (2018) Vienna VLBI and Satellite Software (VieVS) for Geodesy and Astrometry. *Publication of the Astronomical Society of the Pacific*, 130, 044503.
6. Z. Altamimi, P. Rebischung, X. Collilieux, L. Métivier, K. Chanard (2023) ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions. *Journal of Geodesy*, 97:47.
7. A. de Witt, C. S. Jacobs, D. Gordon, M. Bietenholz, M. Nickola, A. Bertarini (2023) The Celestial Reference Frame at K Band: Imaging. I. The First 28 Epochs. *The Astronomical Journal*, 165:139.
8. P. Charlot, on behalf of the IAU Multi-waveband ICRF Working Group (2024) Towards a multi-waveband optical-radio ICRF. *This volume.*