Geodetic Analysis of K-band VLBI Observations Until 2024.0

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Abstract We performed a geodetic analysis of K-band (24 GHz) VLBI sessions from May 2002 until September 2023. For this study, we ran a global solution by adjusting the time-independent parameters from the K-band and S/X sessions (1979.5–2024.0) through a single inversion of all observations. Therefore, we are able to provide the positions of the non-geodetic antennas KVNUS, KVNYS and Mopra for the reference epoch 2015.0 with their linear velocity, which are aligned to the ITRF2020. Formal errors of the position component estimates are below 0.8 cm for the KVN antennas and about 2 cm for Mopra. The components of station linear velocity were estimated with formal errors 0.1 mm/y for KVN antennas and lower than 0.5 mm/y for Mopra. Furthermore, we focus on the potential of the K-band VLBA network for Earth orientation monitoring. We present the accuracy of the Earth orientation parameters computed from the K-band sessions with respect to the a priori IERS values and compare them with the accuracy obtained from the traditional S/X observations.

Keywords VLBI, VLBA, KVN, Mopra, K-band, EOP, station position

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1 Introduction

The Very Long Baseline Array (VLBA; Napier 1995 [7]) astrometric observations at K-band (24 GHz) with the primary objective of extending the celestial reference frame to higher frequencies for improved spacecraft navigation were launched in 2002 (Lanyi et al., 2010 [6]), and then continued to identify additional sources in the Galactic plane region suitable for use as phase calibrators (Petrov et al., 2011 [9]).

In 2013, a new collaboration was formed to continue the astrometric observations of active galactic nuclei (AGN) at the 24 GHz, improving the astrometric accuracy of the K-band catalog. The radio bright AGN in the Deep South were observed with a single baseline between the two 26-meter antennas in Hartebeesthoek (Hh) and Hobart (Ho). In 2023, new antennas joined this K-band project[1], forming another observing network with the core being the Korean VLBI Network (KVN). The KVN+ sessions are irregularly augmented by the 26-meter HartRAO antenna located in South Africa, the 22-meter Mopra antenna in Australia, the 22-meter Sejong geodetic antenna in Korea, and the 40-meter Yebes antenna in Spain.

The positions of KVN antennas, KVNUS (Ulsan) and KVNYS (Yonsei), and Mopra are not included in the International Terrestrial Reference Frame (ITRF2020; Altamimi et al., 2023 [1]) because they haven't participated in the geodetic IVS programs. In the past, estimation of a position offset from a non-IVS VLBI single session adjustment was done for the Mopra antenna for epoch 2007-July-24 by Petrov et al. (2009) [8].

[1] https://sites.google.com/sarao.ac.za/k-bandastrogeovlbi

In this paper, we ran a special common global solution of K-band and S/X sessions to align their positions and linear velocities to the global terrestrial reference frame.

2 Data

In this solution, 203 24-hour K-band databases from May 2002 to September 2023 are included. We count here available RCP and LCP databases from one session as two. For the rest of the sessions, RCP only polarization was recorded. There are the following groups of K-band sessions:

- 102 VLBA sessions (150 databases),
- 38 single baseline sessions Ho-Hh (augmented by TIANMA65 and TIDBIN64),
- 4 single-baseline sessions Ys-Hh (8 databases), and
- 7 KVN+ sessions.

The available 24-hour S/X sessions provided by the IVS Data Centers as the vgosDB version 4, start in August 1979 and we included 7,369 of them until December 2023.

3 Analysis

The analysis is done with the software package VieVS (Böhm et al., 2018 [2]), where we model the delays and adjust them with the least-squares method as described in Krásná et al. (2023a [4], 2023b [5]).
The main setup options are:

- A priori TRF: ITRF2020
- A priori CRF: ICRF3-sx
- A priori EOP: finals2000A.all
- Trop. mapping functions: VMF3 (h+w)
- Iono. calibration for K-band with JPL GPS maps until 2019.1, and CODE ionex maps after 2019.1
- Elevation dependent weighting

The prepared session-wise normal equation systems are adjusted in VIE_GLOB without any further discrimination between K-band and S/X, and among others, the following parameters are estimated:

- TRF offsets and linear velocities as global parameters (epoch 2015.0)
- CRF offsets as global parameters
- EOP as arc-parameters

The datum is defined with an NNT/NNR on 22 station coordinates and velocities w.r.t. ITRF2020, and with an NNR condition on 301 defining ICRF3 sources w.r.t. ICRF3-sx.

Because the antennas KVNUS, KVNYS, and Mopra joined the K-band sessions in 2023, we have to tie their velocities to some nearby antennas in order to be able to extrapolate their velocities to the reference epoch 2015.0. Therefore, the velocities of KVNUS and KVNYS are tied to Sejong (120 km distance from KVNYS), and the velocity of Mopra to the Parkes 64-m antenna in Australia (200 km distance). The time span of the available observations at the discussed antennas included in the solution is the following: KVNUS and KVNYS 2023:078–2023:255, Sejong 2014:273–2023:346, Mopra 2023:084–2023:255, and Parkes 1992:145–2016:223 [yr:doy].

4 Results

The estimated absolute positions for the reference epoch 2015.0 and the linear velocities with their formal errors are listed in Table 1. The estimated velocities can be compared to the velocities of nearby GNSS stations. The GNSS time series published by JPL[2] provide the XYZ components of the linear velocity for YONS (6 km distance from KVNYS) as $[-28.9 \pm 0.7, -13.3 \pm 0.8, -9.2 \pm 0.7]$ mm/yr from measurements starting on 2012:150 to 2024:027, and for the GNSS receiver PARK (200 km distance from Mopra) its velocity components in the XYZ system are $[-35.2 \pm 0.6,\ -1.9 \pm 0.4,\ 47.0 \pm 0.5]$ mm/yr computed from 2006:001 to 2024:027.

In Figures 1–3, the estimated absolute positions of KVNUS, KVNYS, and Mopra in the XYZ system for the reference epoch 2015.0 are plotted, and the black line represents the linear velocity component. The session-wise estimates of the position from the individual available K-band sessions are plotted in blue. With these plots we evaluate the positions of the antennas obtained in the global reference frame solution with the positions obtained from each separate session independently.

[2] https://sideshow.jpl.nasa.gov/post/tables/table1.html

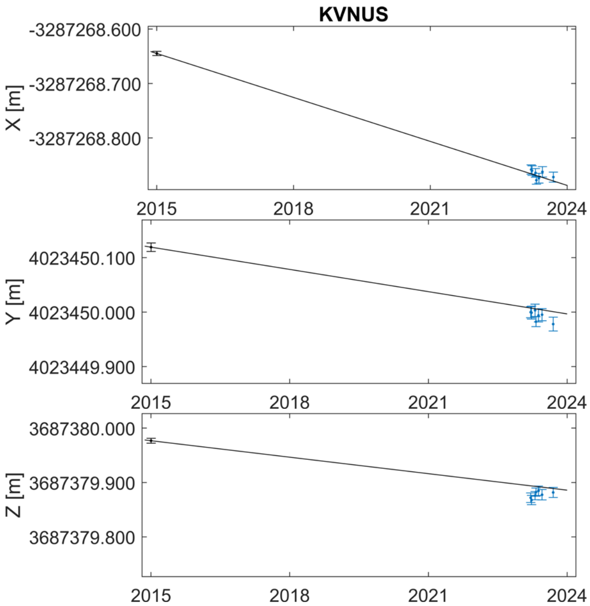

Fig. 1 Absolute position of KVNUS in the XYZ system. The reference position for epoch 2015.0 is given together with the linear velocity from the global adjustment in black. The session-wise estimates from respective K-band sessions are plotted in blue.

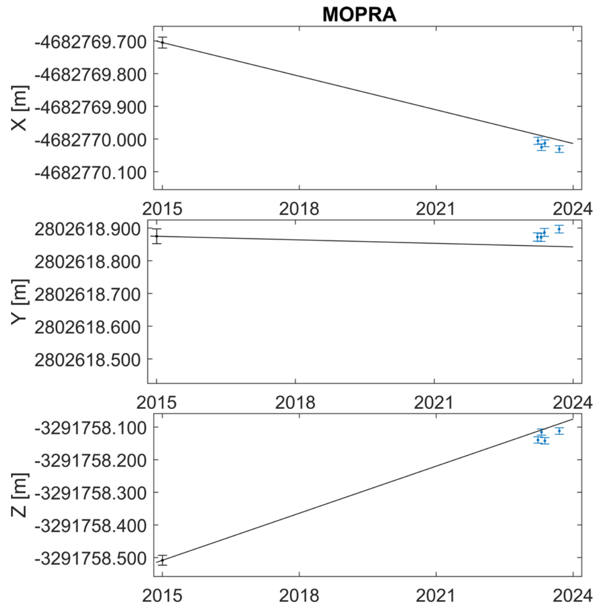

Fig. 3 Absolute position of antenna Mopra in the XYZ system. Description see Figure 1.

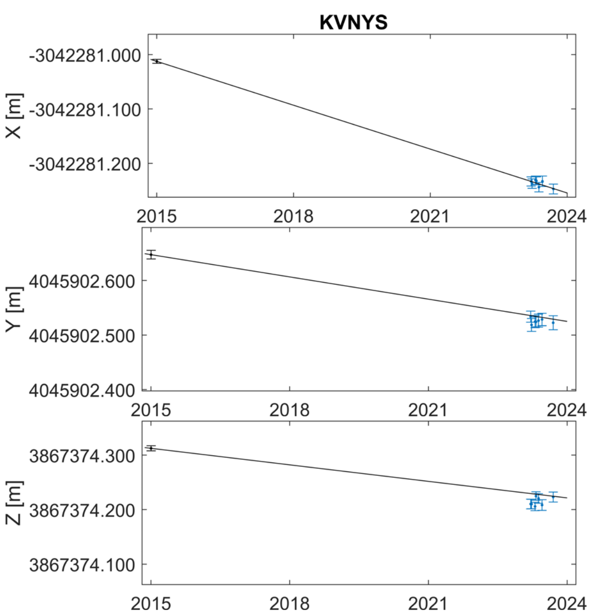

Fig. 2 Absolute position of antenna KVNYS in the XYZ system. Description see Figure 1.

This global solution of S/X and K-band sessions also gives the opportunity to evaluate the EOP from the individual sessions with respect to the common TRF and CRF. In Figure 4 are included time series of all five EOP from S/X sessions (black dots) and K-band sessions (purple diamonds). The Earth rotation parameters (x-pole, y-pole, UT1–UTC) are plotted w.r.t. IERS 20 C04 values, and the celestial pole offsets (dX, dY) w.r.t. nutation-precession model IAU 2006/2000A. In Figure 5 we show statistics for Earth rotation parameters time series estimated from 1) K-band VLBA sessions, 2) S/X VLBA USNO-CRF sessions (i.e., UG002, UG003, and UH007 since 2018.0), 3) S/X rapid R1 and R4, 4) S/X EURO sessions, and 5) all S/X large networks in the solution. The box plots depict the median value of the time series, lower and upper quartiles, maximal and minimal corrections, and outliers which are defined as values more than 1.5 times of the interquartile range away from the top or bottom of the box. In Table 2 we present the statistical values for the K-band sessions divided in three groups according to their data rates. Before 2015 the data rate was 128–256 Mbps, then the rate increased to 2 Gbps, and since November 2019 the rate is 4 Gbps. On the other hand, it should be mentioned that in the recent years the solar activity has increased, putting higher demands on the crucial external ionospheric correction. In Table 3 we summarize the statistics for two groups of S/X VLBI programs: 1) USNO-CRF sessions observed with VLBA since 2018.0, and 2) rapid IVS EOP sessions R1 and R4 starting in 2002.0.

Table 1 Station positions at epoch 2015.0 and linear velocities with their formal errors.

	X [m]	Y [m]	Z [m]	Vx [mm/y]	Vy [mm/y]	Vz [mm/y]
KVNUS	−3287268.645 ± 0.004	4023450.119 ± 0.008	3687379.977 ± 0.005	−26.9 ± 0.1	−13.6 ± 0.1	−10.1 ± 0.1
KVNYS	−3042281.013 ± 0.004	4045902.647 ± 0.008	3867374.312 ± 0.005	−26.9 ± 0.1	−13.6 ± 0.1	−10.1 ± 0.1
MOPRA	−4682769.705 ± 0.017	2802618.875 ± 0.023	−3291758.509 ± 0.015	−34.3 ± 0.5	−3.6 ± 0.3	48.1 ± 0.4

Table 2 Statistics on EOP estimated from K-band VLBA sessions w.r.t. IERS 20 C04. The statistics are computed for three groups of K-band VLBA data according to their data rates: before 2015 / 2015-Nov2019 / after Nov2019, which corresponds to: 128–256 Mbps / 2 Gbps / 4 Gbps.

K-band: 128–256 Mbps / 2 Gbps / 4 Gbps	x_p [µas]	y_p [µas]	UT1–UTC [µs]	dX [µas]	dY [µas]
median	−112 / −3 / −115	361 / −83 / −37	−31 / −5 / 8	−33 / 1 / 64	0 / −70 / 12
weighted mean	−23 / −83 / −113	382 / −167 / 8	−17 / −2 / 17	25 / 6 / 64	33 / −71 / 16
wrms	250 / 239 / 312	279 / 448 / 339	33 / 22 / 34	129 / 137 / 164	112 / 122 / 168
mean formal error	223 / 103 / 89	232 / 110 / 95	19 / 7 / 7	85 / 52 / 44	96 / 51 / 41
median of abs. deviation	198 / 157 / 233	314 / 333 / 148	22 / 14 / 25	97 / 107 / 112	80 / 116 / 110

Table 3 Statistics on EOP estimated from S/X-band VLBA sessions USNO-CRF since 2018.0 (UG002, UG003 and UH007), and S/X-band R1 and R4 sessions since 2002.0. The statistics are computed w.r.t. IERS 20 C04.

SX-band: USNO-CRF / R1,R4	x_p [µas]	y_p [µas]	UT1–UTC [µs]	dX [µas]	dY [µas]
median	−114 / −55	−186 / −67	10 / 1	47 / 31	−49 / −3
weighted mean	−186 / −60	−165 / −69	11 / 1	28 / 34	−61 / −1
wrms	353 / 151	464 / 166	36 / 10	156 / 84	220 / 87
mean formal error	131 / 89	138 / 87	11 / 4	61 / 49	65 / 50
median of abs. deviation	211 / 107	262 / 113	22 / 7	97 / 53	124 / 53

The statistics comparing the EOP estimated with the VLBA network show comparable results from the K-band and S/X-band. In both cases, the main focus of the VLBA programs is the celestial reference frame. The wrms of ERP w.r.t. IERS 20 C04 are slightly lower for K-band. For the last group of K-band sessions from November 2019 to September 2023 the wrms values are: x-pole: 312 µas, y-pole: 339 µas, UT1–UTC: 34 µs. The wrms from the S/X USNO-CRF sessions are: x-pole: 353 µas, y-pole: 464 µas, UT1–UTC: 36 µs. The dedicated IVS R1 and R4 sessions for the rapid EOP estimation show superior wrms probably on account of the better network geometry and other scheduling goals: x-pole: 151 µas, y-pole: 166 µas, UT1–UTC: 10 µs.

5 Conclusions

We computed absolute positions of KVN antennas Ulsan and Yonsei, and Mopra for the reference epoch 2015.0 together with the linear velocities consistently in a global VLBI terrestrial reference frame. The KVN antennas were estimated with a formal error lower than 8 mm for each of the XYZ components. The formal errors are below 2 cm for Mopra. The EOP from K-band and S/X-band observations are estimated w.r.t. the consistent TRF and CRF computed in a single global adjustment. Comparing the EOP estimated from the VLBA sessions, all focused on the celestial reference frame, the statistics show comparable results between the K-band and S/X-band.

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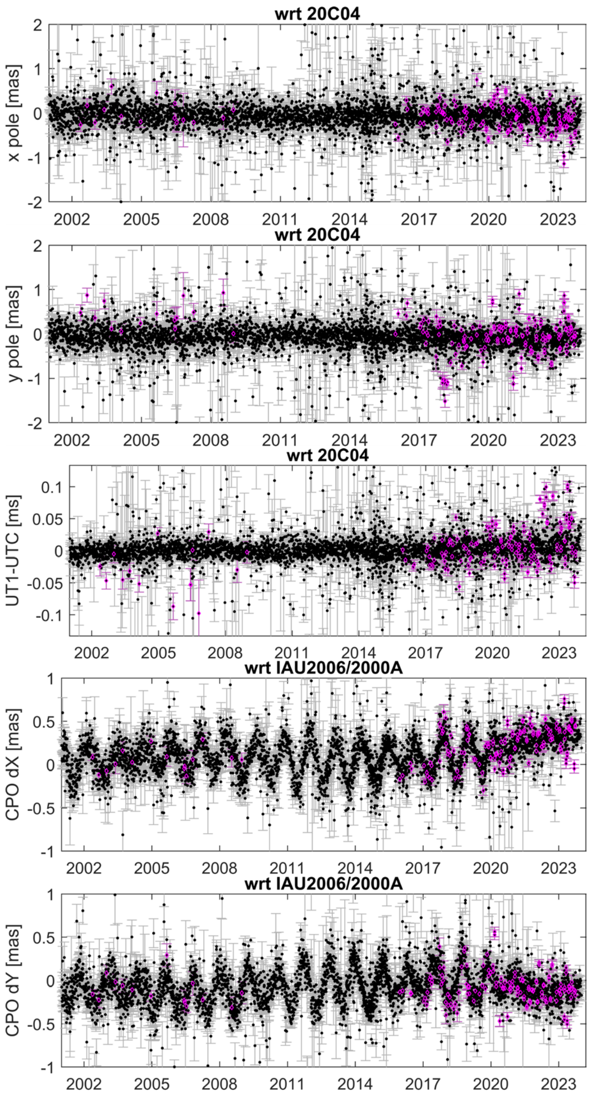

Fig. 4 Time series of all five EOP from S/X sessions (black dots) and K-band sessions (purple diamonds).

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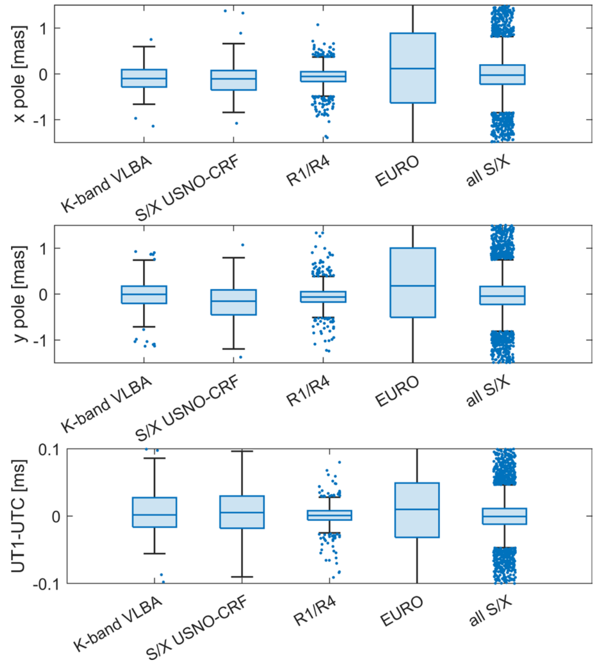

Fig. 5 Statistics of the Earth rotation parameters w.r.t. IERS 20 C04 values for individual observing programs.