K-band 24-hour EOPs and UT1–UTC Intensives

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Abstract We investigate the potential for EOP and UT1–UTC measurements at K-band (24 GHz). A 'K-band Collaboration' has been making regular VLBA K-band astrometry sessions since 2016 for expansion and improvement of the ICRF at K-band. Since 2017, these sessions have been made approximately monthly under the U.S. Naval Observatory's VLBA 50% time allocation. Though designed for astrometry, these 24-hour sessions also yield accurate EOP measurements. We will compare the K-band EOPs with various other series, such as the IERS C04 series, USNO's legacy S/X (2.3/8.4 GHz) series from IVS data, and a USNO series from VLBA S/X astrometry sessions. Over the next few years, the ten VLBA antennas will be equipped with broadband receivers capable of observing from 8 to 40 GHz and could thus simultaneously observe at X/K- or X/Ka- or even X/K/Ka-bands, allowing better ionosphere calibration than the current application of ionosphere corrections from GNSS ionosphere maps. To explore the potential for K- or X/K-band UT1–UTC measurements, we ran a series of four four-hour VLBA K-band UT1–UTC Intensive-type sessions, in July 2023, spaced one week apart. We have processed these into sets of 16 one-hour single-baseline databases for several long baselines. We will show the comparison of the UT1–UTC solutions and formal errors versus other UT1–UTC series, such as the IVS S/X UT1–UTC series and USNO's VLBA UT1–UTC series.

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1 Introduction

Intensive observations, which are short duration, single-baseline observations using radio Very Long Baseline Interferometry (VLBI), are essential for precise measurements of the rotation rate of the Earth. These observations have most commonly been made using a dichroic system that enables observations of radio bright quasars at 2.3 GHz (S band) and 8.4 GHz (X band) simultaneously. This dual-band method enables an accurate calibration of the Earth's ionosphere, which can add delays to the path length of the quasar light to the radio antenna, thus degrading the precision of the measurement. Our ever-changing technological world is imposing more and more demands on the radio frequency spectrum for use to support technologies such as telecommunications. Such demands from the commercial sector have caused a stark increase in radio frequency interference (RFI) of astronomical observations of celestial objects. The most affected parts of the radio spectrum currently are the 1 to $\sim$5 GHz range. This provides strong motivation to move astronomical observations of quasars for astrometric and geodetic monitoring to higher frequency parts of the radio continuum band where the spectrum is less affected by RFI.

K-band observations near 24 GHz are becoming an increasingly more useful and interesting spectral region for celestial reference frame (CRF) monitoring, and this region of the radio band has additional benefits to a lower RFI environment, including a lower ionosphere contribution and, in theory, less source structure of the quasars themselves compared to observations made at lower radio frequencies (de Witt et al. 2023). However, there is a water absorption line at 22 GHz, which makes observations at these frequencies more sensitive to weather and moisture in the atmosphere. Currently, all K-band CRF data are unable to be simultaneously observed at a lower frequency for calibration of any residual ionosphere delay; so instead, total electron count (TEC) maps such as those produced by the Jet Propulsion Laboratory (JPL) are the only readily available calibration dataset. These TEC maps are averaged over two hours and thus do not fully calibrate K-band observations. The United States Naval Observatory (USNO) has secured funding for a suite of wideband, 8–40 GHz, receivers (Kooi et al. 2023) to be deployed across all ten stations of the Very Long Baseline Array (VLBA), which will enable new capabilities such as simultaneous observations of 8 and 24 GHz for improved ionosphere calibration.

Here, we present initial results from a K-band Intensive campaign that was observed with the VLBA in July 2023 through the USNO's 50% timeshare allocation. We also present an independent analysis of the K-band 24-hour sessions analyzed using νSolve and Calc/Solve software provided by the Goddard Space Flight Center, and we compute Earth Orientation Parameters (EOPs) from these data. We compare the EOPs from K-band results to the legacy dual S/X (2.3/8.4 GHz) Intensive and diurnal observations.

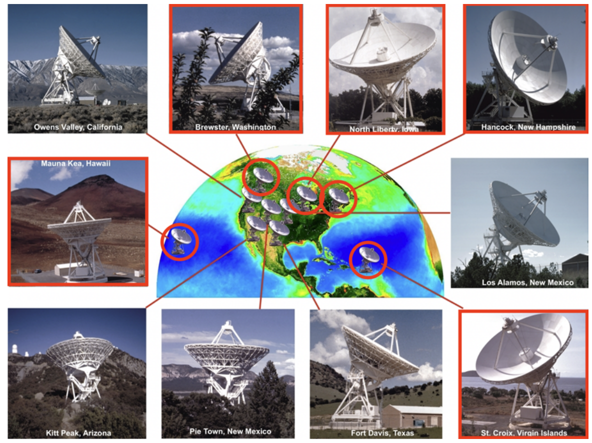

Fig. 1 Very Long Baseline Array highlighting the five stations used in the Intensive observations at K-band.

2 Data

The K-band observations were observed on the VLBA using dual-circular polarization across four consecutive 128-MHz intermediate frequency (IF) channels starting at 23.312, 23.440, 23.568, and 23.696 GHz, respectively. During the data analysis, we discovered that there was an additional path length delay in the left circular polarization (LCP) feed compared to the right circular polarization (RCP) feed. Therefore, we only used the RCP data throughout our analysis.

The 24-hour diurnal sessions have been observed at K-band with the VLBA for over 20 years. To date, no analysis of the EOPs from these observations has been published. To explore the implications of using K-band data for producing EOPs, we analyze the 24-hour diurnal sessions and compare the results to the EOPs derived from the legacy S/X band data. In addition, we compare four four-hour Intensive-style sessions obtained on the VLBA in July 2023. These data were obtained using all ten VLBA antennas. We made databases using all ten stations from the total four hours of observing time per each of four sessions that were separated by one week. We also analyzed databases that were fringed over one hour to produce four sessions per observation with five of the antennas, namely, Mauna Kea (Mk), Brewster (Br), North Liberty (Nl), Hancock (Hn), and St. Croix (Sc). Further, we fringed the data to separate out the five stations into single baselines for a more apples-to-apples comparison of the S/X Intensive series that USNO observes on the VLBA. Figure 1 shows the five antennas that were analyzed for UT1–UTC. We selected the stations that extended furthest in the east-west direction but also had a northern reaching geometry. Schartner et al. (2021) explains the ideal geometry of Intensive baselines from a theoretical perspective, and we aimed to select stations that most closely resembled this ideal east-west with a northern reach geometry. Table 1 shows the sessions analyzed here in this work.

Table 1 VLBA 24-hour diurnal and Intensive K-band sessions. All data are open access except for UD017 and can be downloaded from the NRAO archive at https://data.nrao.edu. Session UD018 is the Intensive series.

Session Codes	Dates of Observations	Reference
BR079, BL115, BL112	2002–2007	Lanyi et al. 2010
BJ083 A–D, A1	Jul 2015 – Jun 2016	de Witt et al. 2023
UD001 A–X	Jan 2017 – Jul 2018	de Witt et al. 2023
UD009 A–AH	Sep 2018 – Jun 2021	de Witt et al. 2023
UD015 A–R	Jul 2021 – Jan 2023	de Witt et al. 2023
UD017 A–P	Jan 2023 – Dec 2023	de Witt et al. 2023
UD018 A–D	Jul 2023	...

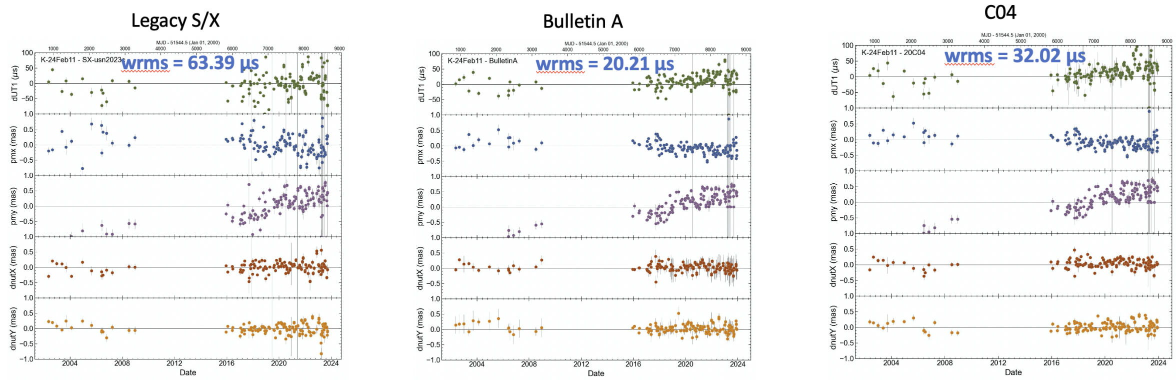

Fig. 2 EOP residuals of 24-hour K-band diurnal sessions compared to S/X data from usn2023c global solution, Bulletin A, and IERS C04.

3 Analysis

The K-band data were analyzed using νSolve and Calc/Solve software; however, because there is no dichroic system available on VLBA with the K-band receiver, ionosphere calibrations were performed using TEC maps provided by the JPL. These TEC maps are averaged over two hours and therefore can only do a coarse ionosphere calibration over the short duration Intensive sessions. Figure 2 shows the residuals of the EOPs determined from the 24-hour diurnal sessions compared to three different S/X series: the S/X series from the USNO 2023c global solution (usn2023c), the Bulletin A series produced weekly by the USNO combinations and predictions center, and the IERS C04 series produced monthly by the Observatory of Paris. The weighted root mean square (wrms) of the UT1–UTC EOP parameter is shown in blue text at the top of each plot in units of μs. The remaining wrms values for each of the other EOPs are shown in Table 2.

We find good agreement between the K-band EOP values and the S/X series. The y-coordinate residuals of the polar motion (PM_Y) shown in purple in each plot in Figure 2 show a slope of unknown origin. This slope is likely attributed to the lack of southern hemisphere observations. Figure 3 shows the residual EOP values from the K-band 24-hour sessions again, but this time overlaid onto the legacy S/X residuals as compared to the IERS C04 series. This figure visually shows good

Table 2 VLBA 24-hour diurnal K-band session residual statistics showing the weighted mean and weighted median for each parameter compared to the reference series.

Reference Series	Statistic (wt.)	UT1–UTC (μs)	PM_X (mas)	PM_Y (mas)	$dNut_X$ (mas)	$dNut_Y$ (mas)
K values	mean	−0.05	0.12	0.35	0.23	−0.04
	median	−0.10	0.10	0.34	0.25	−0.06
K vs. Bull. A	mean	13.12	−0.10	0.13	0.07	0.03
	median	13.30	−0.09	0.14	0.09	0.03
K vs. 20C04	mean	27.36	−0.11	0.15	0.04	0.04
	median	21.53	−0.11	0.15	0.05	0.02
K vs. S/X	mean	−0.77	−0.04	0.03	0.02	0.01
	median	−1.10	−0.07	0.05	0.02	0.01

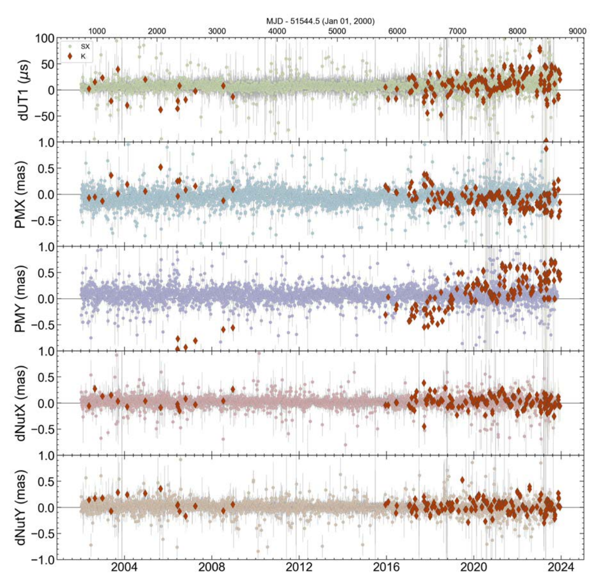

Fig. 3 EOP residuals for the K-band 24-hour diurnal sessions compared to the legacy S/X band data from the C04 series.

agreement between the K-band and S/X EOPs, aside from the slope in the PM_Y parameter.

The four four-hour Intensive sessions that were observed in July 2023 were inadequate for a full statistical analysis such as we performed on the 24-hour diurnal sessions. However, we used these data to compare K-band derived Intensives to the IVS S/X Intensives from the single baseline comprised of the Kokee Park 20-meter (Kk) and Wettzell 20-meter (Wz) antennas. Figure 4 shows the K-band UT1–UTC residuals as compared to the IERS C04 series overlaid onto the S/X Intensive residuals. The yellow points are the UT1–UTC values derived from K-band for all ten VLBA antennas over the full four-hour session. The red points are the single-baseline observations at K-band for just the Mk–Hn baseline over a single hour, which is why there are four points per epoch shown on the plot. These points are overlaid onto the

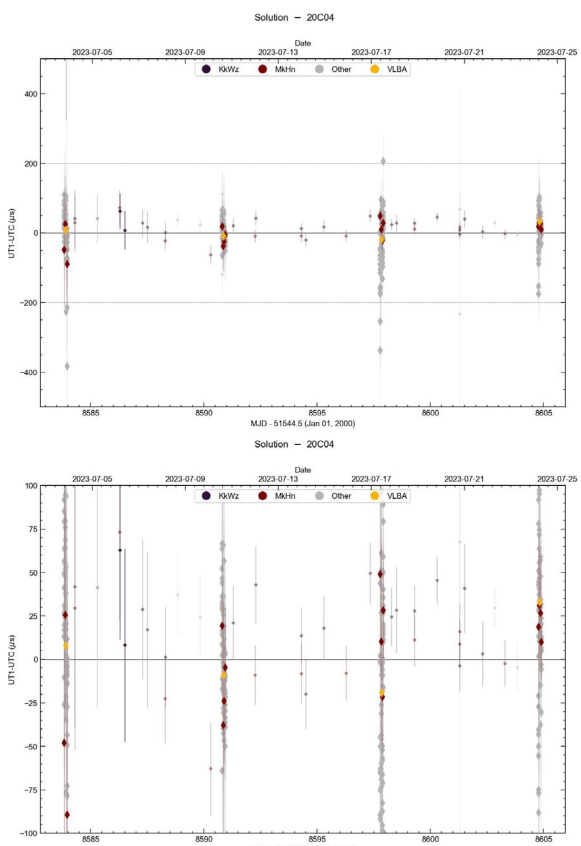

Fig. 4 UT1–UTC residuals for the K-band Intensive sessions compared to the legacy S/X band data from the C04 series. The bottom plot is a zoomed in version of the top plot for clarity.

Kk–Wz baseline, and, again, we find good agreement between the two data series as compared to IERS C04. Improvements in these measurements may come from improved ionosphere calibrations, which will be possible with the JPL 8–40 GHz wideband receivers (Kooi et al. 2023) where simultaneous X and K-band measurements can be made. A longer K-band Intensive time series and exploring the effects of seasonal changes on UT1–UTC are logical next steps in the analysis of K-band Intensives.

4 Conclusions

K-band observations on the VLBA can be used for EOP measurements. We find comparable trends in the residuals of K-band 24-hour sessions as in the legacy S/X sessions, which is promising for continued work in K-band EOP observations. We find that K-band Intensive-style observations on the VLBA produce similar residual UT1–UTC values as the S/X legacy Intensive data. Looking forward, pursuing a longer-term Intensive series at K-band to explore changes throughout a year and to work on improving the ionosphere calibrations is reserved for future work. The JPL 8–40 GHz wideband receivers (Kooi et al. 2023) will be useful for observing X and K-bands simultaneously, which should improve the ionosphere calibrations and thus produce more precise EOPs. It is important to note that the VLBA station positions and velocities determined with K-band data have not been analyzed and compared to the station coordinate vectors as determined in the S/X band; so, we look to future efforts to analyze these parameters systematically.

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