Completing the K-band Celestial Reference Frame in the Southern Hemisphere

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Abstract K-band (22 GHz) radio observations have the potential to form the basis for the most accurate Celestial Reference Frame (CRF) ever constructed. Relative to the standard S/X (2.3/8.4 GHz) observing bands, K-band is expected to exhibit a reduction in extended source morphology and core-shift. This reduction in astrophysical systematics should allow for a more stable CRF at K-band and should also be advantageous in tying the VLBI radio frame to the Gaia optical frame. K-band CRF observations currently exist only from the all-northern Very Long Baseline Array (VLBA) and therefore must be complemented by observations from southern arrays in order to realize this potential. A collaboration was formed with the goal of completing sky coverage at K-band with specific emphasis on the Southern hemisphere where K-band CRF coverage is weak. Southern hemisphere observations to densify the CRF at K-band are under way and preliminary astrometric observations were carried out on 23 August 2013 between telescopes in Australia (Hobart 26 m), Korea (Tamna 21 m), and South Africa (HartRAO 26 m). More extensive astrometric observations were carried out on 21/22 December 2013 that also included the Tidbinbilla 70-m DSN antenna in Australia. A proposal for imaging source structure at K-band has been submitted to the Australian Telescope-Long Baseline Array (AT-LBA). We discuss some of our results as well as the implications for K-band CRF work.

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Keywords Celestial Reference Frame, VLBI, astrometry, K-band, quasar

1 Introduction

In recent years, VLBI radio source angular position accuracy has improved to the sub-milliarcsecond level. High precision VLBI measurements of positions of extragalactic radio sources define and maintain the current International Celestial Reference Frame (ICRF-2, [10]), which forms the underlying basis for positional astronomy. The ICRF-2 is based on dual frequency S-band (2.3 GHz) and X-band (8.4 GHz) VLBI observations of 3,414 reference sources. Catalogs of positions of extragalactic radio reference sources with the highest precision are needed for many applications. Among these are imaging of faint radio sources in phase-referencing mode, accurate differential astrometry, spacecraft tracking, space navigation, and space geodesy. Extragalactic radio sources that are relatively bright at the frequency of observation, compact, or core-dominated on VLBI scales and that have no or little detectable motion are well-suited for high-accuracy reference frame work. Quasars, being at great distances, do not exhibit any measurable proper motion or parallax, making them ideal reference sources.

Unfortunately, at the standard S/X frequencies, many ICRF sources exhibit spatially extended intrinsic structures that may vary with time, frequency, and baseline projection. This departure from the pointsource approximation commonly made in astrometric VLBI analysis can have a significant effect on the measured VLBI positions. Extended source structures, if not corrected for, will limit the ability to further improve the accuracy of individual VLBI source positions and thus the improved stability of future celestial reference frames (CRFs). However, mapping the structures on a regular (approximately monthly) basis for hundreds of sources has proven to be too resource intensive to be a sustained solution.

Our solution is to observe at higher radio frequencies such as K-band (22 GHz), where, on VLBI scales, sources tend to be more compact (e.g., [1] and [2]), and hence the structure effects on astrometric position estimation should be reduced. VLBI observations of quasars have also shown that the location of the peak brightness often varies with observing frequency due to opacity effects, a phenomenon known as "core-shift". In particular, VLBI images of quasars show that the observed position of the peak brightness moves closer to the central black hole as the frequency increases (e.g. [13]). Thus by observing at frequencies higher than the standard S/X bands, we can expect to see more compact structure and also reduce the effect of core shift [7]. This reduction in astrophysical systematics should allow for a more accurate and stable reference frame at these higher frequencies and be particularly advantageous in tying the VLBI reference frame to future optical reference frames such as Gaia.

2 Reference Frames at Higher Radio Frequencies

At present there are far fewer observations of extragalactic reference sources at high radio frequencies compared to the standard S/X observing bands. One of the major challenges of observing at higher radio frequencies is the decrease in system sensitivity. At higher radio frequencies, the sources themselves are in general weaker and many sources are resolved, antenna performance (e.g. antenna pointing) becomes degraded, system temperatures are higher and more susceptible to degradation from bad weather, and coherence times are shorter. Fortunately the rapidly decreasing costs of recording higher data rates allows us to compensate for sensitivity issues that result from observing at higher radio frequencies. In the last few years, considerable work has been done and significant progress made on defining reference frames at higher radio frequencies.

Astrometric VLBI observations at Ka-band (32 GHz), a combined project of NASA's Deep Space Network and ESA, have already developed a catalog of ~ 631 observable sources (134 south of $-45°$ declination) with highly accurate positions for improved deep-space navigation [6], showing that there are sufficient strong sources suitable for astrometric use at higher frequencies. However, all the data from the Ka-band effort is from single baseline passes only, and thus no source images could be made. Astrometric and imaging observations by Lanyi et al. [8] and Charlot et al. [2] provided a foundation for the development of a reference frame at K-band. The current K-band frame consists of only 279 sources with weak coverage in the southern hemisphere, showing a rapid drop in source density at declinations south of $-30°$.

Because many stations across the globe have K-band receivers, there is now an opportunity to create a worldwide K-band network with potential for high resolution imaging and astrometry. The advantage of observing at K-band is that radio observatories typically have K-band receivers, while Ka-band receivers are typically only available at tracking stations, which are very few in number. For very long baseline observations at K-band, calibrator reference sources are also needed, in particular for trigonometric parallax distances to H_2O (22 GHz) masers (e.g. [12]), as well as phase referenced observations to image the sub-milliarcsecond structure of the most compact regions of emission in AGN. High-resolution K-band observations would also be of much value to study wavelength dependent systematic errors due to the core-shift effect.

3 Why Observe in the Southern Hemisphere?

VLBI observations in the southern celestial hemisphere have always been more difficult both because there are fewer radio telescopes in the south than in the north, and because there are fewer known reference sources in the south. There have been many efforts in recent years to increase the number of known calibrator reference sources in the south, in particular the Australian Telescope - Long Baseline Array (AT-LBA) calibrator survey (LCS), which has already produced a significant improvement at X-band [11]. There have also been a few observations at S-band, for example, Hungwe et al. [5], and southern observations are planned at 1.6 GHz (L-band), to improve the number of calibrator sources for phase-referencing at low frequencies. In 2012, an International Astronomical Union (IAU) working group was formed with the goal of the realization of the next generation International Celestial Reference Frame (ICRF-3), with specific emphasis on improving the accuracy and coverage in the southern hemisphere. Dedicated astrometric observations to improve the southern celestial reference frame at S/X band are currently underway, as proposed in Lovell et al. [9]. However, at present there are virtually no VLBI observations of reference sources at K-band. All these low frequency programs thus invite complementary work at K-band.

4 Observational Plan and Network Geometry for Southern Hemisphere VLBI at K-band

We have undertaken a program to observe potential K-band reference sources in the Southern Hemisphere. These observations are motivated by the need to complete sky coverage at K-band and thus extend CRFs to higher radio frequencies. Astrometric observations to complete sky coverage at K-band, as well as VLBI imaging observations to characterize the nature of the sources at K-band, are underway. Preliminary astrometric observations were carried out on 23 August 2013 between telescopes in Australia (Hobart 26 m), Korea (Tamna 21 m), and South Africa (HartRAO 26 m). More extensive astrometric observations that also included the Tidbinbilla 70 m DSN antenna in Australia were carried out on 21 December 2013, and similar observations are planned for 4 May 2014. Details of the observational setup and preliminary results are presented in Section 5. The Korea to South Africa baselines will extend K-band CRF coverage down to about -45° declination, and observations between Australia and South Africa will extend coverage to the south polar cap and thus gain full sky coverage for the K-band CRF. Observations between Tamna and HartRAO are limited to about $\pm 45^\circ$ declination and less than four hours of mutual visibility.

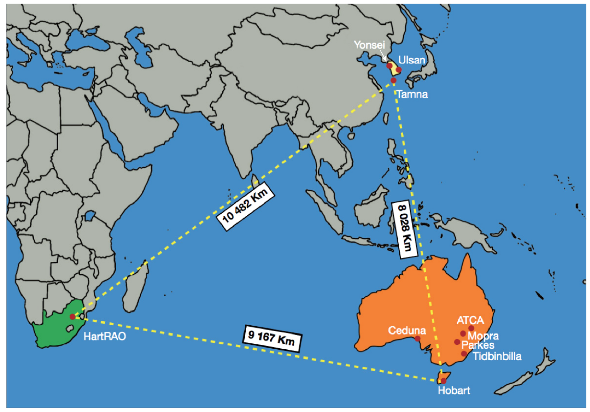

Fig. 1 A map showing the proposed telescopes for the Southern hemisphere K-band observations.

For imaging of source structure, as opposed to astrometry, a larger network of telescopes is needed in order to provide a variety of baseline lengths and orientations. For this purpose we have also submitted a proposal to observe and image a set of potential K-band reference sources at declinations below -30°. We will use the full AT-LBA which adds the ATCA (6-m and 22-m), Ceduna (30-m), Mopra (22-m), and Parkes (64-m) telescopes in Australia to our observing network (see Figure 1). It should be noted, however, that although the AT-LBA provides a large network of antennas, we are still missing intermediate baseline lengths of a few thousand kilometers.

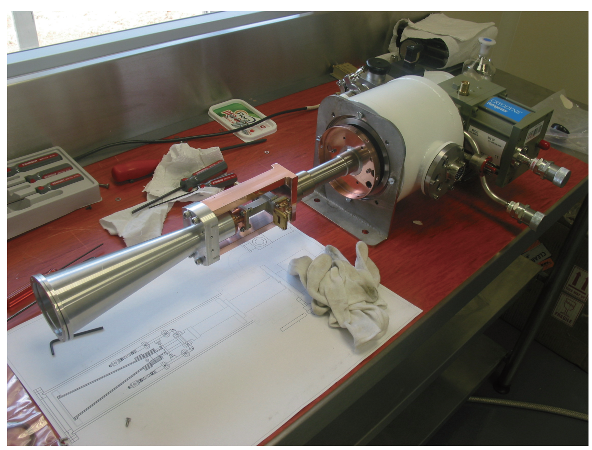

Fig. 2 New cryogenically cooled K-band receiver during development at HartRAO. The feed horn and waveguide components for the receiver were included inside the cryogenic vacuum package and cooled down with the low noise amplifiers. This resulted in a very low receiver noise temperature of 20–25 K.

We have identified the uncooled K-band receiver on the HartRAO 26-m antenna as one of the major error sources in our K-band CRF work and thus made it high priority to develop a cooled receiver. Although the current K-band receiver at HartRAO is VLBI-capable and regularly detects fringes from VLBI observations, it has a high noise temperature (250 K), limiting observations to the brightest sources only (> 500 mJy). A new cryogenically cooled K-band receiver is under development at HartRAO (see Figure 2) to replace the experimental ambient receiver currently on the antenna. The receiver is undergoing lab testing, and we hope to have it installed and ready for VLBI use by the time we run our next K-band observations in May 2014.

5 Observations and Preliminary Results

Our first test observations ran for four hours on 23 August 2013, and about 20 sources from the LCS catalog were observed ([4]) . Given that we found fringes to all stations, we proceeded with a similar 24-hour experiment starting 21 December 2013, in which we observed a total of 106 sources at K-band (see Figure 3).

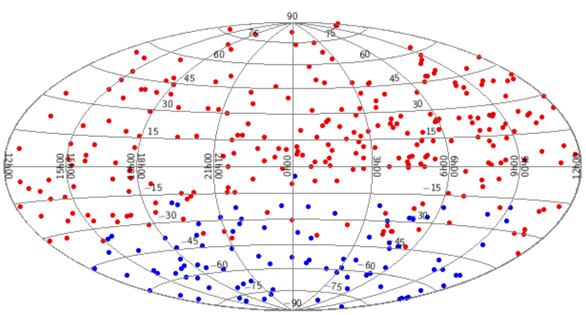

Fig. 3 The distribution of CRF sources at K-band. The 279 sources from Lanyi et al. [8] and Charlot et al. [2] are shown in red. The 106 sources observed at K-band during 21–22 December 2013 are shown in blue. There are 12 overlapping sources.

These observations included also the Tidbinbilla 70-m antenna using their recently installed VLBI digital backend called the Deep Space Station VLBI Processor (DVP) and their old Mark IV terminal for redundancy. The trial correlation proved that data from both the DVP and the KVN digital backend can be successfully correlated using DiFX ([3]). However, inadvertently, after a few scans, the setup of the DVP was changed. This change requires special DiFX modes that are not functional yet; therefore, the correlation is still pending.

Figure 4 shows, as an example, the detection of ICRF J1427-4206 from both observations. Table 1 shows some of the detections on the baseline between Tidbinbilla (Mark IV terminal) and Hobart. One should also keep in mind that the Mark IV rack was observing at half the speed (512 Mbps, instead of 1 Gbps), and only three 16 MHz wide channels were usable, i.e., the bandwidth was reduced from 256 MHz to 48 MHz.

Table 1 SNRs of some of the observed sources in the baseline Tidbinbilla (Mark IV terminal) to Hobart. The flux densities of these sources are not yet available, as no amplitude calibration has been applied yet.

Source	No. Obs	SNR
J0049-5738	1	24
J0058-5659	1	27
J0309-6058	1	12
J0403-3605	1	15
J0519-4546	1	20
J0522-6107	1	8
J0529-7245	1	56
J0550-5732	2	23
J0845-5458	1	22
J1038-5311	1	65
J1147-3812	1	17
J1206-6138	3	15
J1254-7138	2	10
J1515-5559	2	24
J1617-7717	3	22
J1703-6212	1	23
J1834-5856	1	8
J1932-4536	1	8
J1940-6907	1	10
J2056-4714	1	48
J2147-7536	1	40
J2239-5701	1	36

6 Summary and Outlook

As radio frequency increases, sources are expected to exhibit more compact source morphology and reduced core-shift. Astrometric VLBI observations of reference sources at K-band will therefore allow for a more accurate and stable reference frame to be constructed. For this reason, we began an observational program to

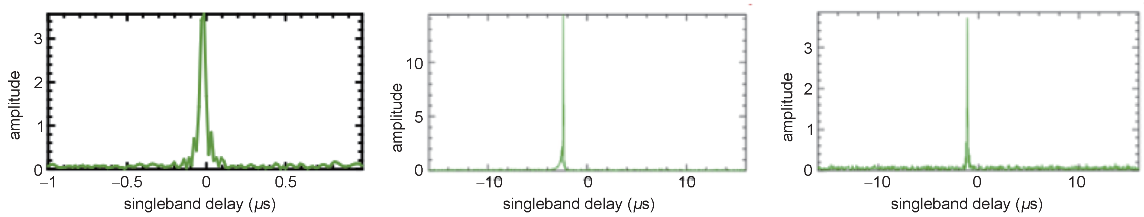

Fig. 4 HOPS fourfit plots, showing the single-band delay for ICRF J1427-4206 betweenHartRAO and Hobart (SNR $\sim$ 70, left) from the August 2013 observations, and the between Hobart and Tidbinbilla (SNR $\sim$ 338, middle) and HartRAO and Tidbinbilla (SNR $\sim$ 95, right) from the December 2013 observations.

densify the CRF at K-band. Our initial focus will be on the Southern hemisphere, where K-band coverage is weak. We have successfully detected fringes from our first test observations to demonstrate the feasibility of our experimental approach. We have also demonstrated that data taken with the KVN digital backend as well as the Tidbinbilla DVP backend system can be successfully correlated with DiFX. The new cryogenic K-band receiver for the HartRAO 26-m antenna, as well as improvements in the instrumental calibration at HartRAO, provides hope that significant progress in the Southern hemisphere is achievable within the next one to two years.

Our goals for K-band are the realization of a full sky CRF by 2018, in time for the Gaia optical reference frame. Our first goal is to obtain comparable density and accuracy in the south to that obtained from the astrometry that was done with the VLBA in the north. The second goal will be further densification of the K-band frame in the north using the VLBA as well as the European VLBI Network (EVN). We will also make use of EVN and HartRAO baselines to improve the accuracy of source positions in declination. Our ultimate goal is to reach accuracies better than 70 μas to match the Gaia predicted accuracy for V = 18 visual magnitude quasars.

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