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Extending the ICRF to Higher Radio Frequencies: 24 and 43 GHz Astrometry

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Abstract

Celestial reference frames have been constructed at K-band (24 GHz) and Q-band (43 GHz) based on VLBI astrometric survey observations of active galactic nuclei. Five VLBA observing sessions covered the full 24 hours of right ascension and declinations down to $-44°$. K-band's 230 sources have median formal position uncertainties of 150 and 290 μas in $\alpha \cos\delta$ and δ, respectively; the corresponding uncertainties for 132 Q-band sources are 215 and 360 μas, respectively. K-band weighted RMS (WRMS) residuals were 33 ps and 48 fs/s in delay and rate, respectively. Comparison of the K-band frame to the S/X-band ICRF shows WRMS agreement of 330 and 590 μas in $\alpha \cos\delta$ and δ, respectively. The motivations for extending the ICRF to higher frequencies are to use more compact sources to construct a more stable frame, to provide phase calibrators, and to support spacecraft navigation at Ka-band.

1. Introduction

Early in the development of the Very Long Baseline Interferometry (VLBI) technique, it was recognized that observations of distant active galactic nuclei had the potential to form the basis of a quasi-inertial celestial reference frame with milli-arcsecond (mas) or better accuracy. In the 1990s, the IAU working group on reference frames created a consensus celestial reference frame known as the International Celestial Reference Frame (ICRF, *cf.* Ma *et al* (1998)) that realized this potential at S/X-band (2.3/8.4 GHz). It was appreciated then that extension of the ICRF to additional frequencies would further enhance the value of the work already done.

A number of developments have now converged to make the present an opportune time to pursue the extension of the ICRF to radio frequencies in the 24–43 GHz range. First, staying at S/X is increasingly threatened by S-band radio frequency interference. Second, low noise amplifiers at K (24 GHz), Ka (32 GHz), and Q-band (43 GHz) are now available for use by the VLBI technique. Third, Boboltz *et al.* (2004) present evidence that sources are more compact—and therefore more astrometrically stable—at these frequencies than at X-band. Thus there is potential for a frame that is superior to the current S/X-based ICRF. Fourth, radio systems for planetary probes are moving to Ka-band and are expected to require sub-mas tracking accuracy. Interpolating the K and Q-band results will provide initial constraints on astrometric suitability of sources at Ka-band thereby allowing one to build a roadmap for high accuracy spacecraft navigation at 32 GHz.

Our long term goal is to move from simultaneous dual frequency S/X-band to X/Ka-band. Ka-band allows for higher telemetry rates to spacecraft and reduces plasma errors by a factor of

≈ 16 compared to X-band. Eventually we will move our focus away from single band K or Q-band work to simultaneous X/Ka-band work. In the meantime, we must rely on K and Q-band results.

2. Observations

The results presented here are based upon five VLBA sessions: 15 May 2002, 25 August 2002, 26 December 2002, 22 May 2003, and 13 September 2003. The first two sessions observed the same set of 65 sources which was selected based on predicted compactness and strength of flux (typically > 0.7 Jy). The third session extended observations to weaker sources; the fourth session was a K-band only survey which nearly doubled the number of sources observed in that band; the 5th session returned to observing both K and Q-bands. Each source was observed with 3–5 snapshots, each of which used the entire array for 2 minutes at K-band and then 2 minutes at Q-band (except for session 4). This strategy was chosen to allow adequate uv coverage for simultaneous imaging while still permitting sub-mas global astrometry based on group delays over a 400 MHz spanned bandwidth. Recorded bandwidth was 128 Mbps. There were 36204 usable pairs of delays and rates which were fit with 1388 degrees of freedom. The VLBA is limited to U.S. territory by design. The longer baselines contribute proportionately more to the astrometric solution. The array has a greater East-West extent compared to its North-South extent. As a result, the VLBA produces better precision in right ascensions than declinations by a factor of ≈ 1.5.

3. Results

Data from our five sessions yielded a global reference frame of right ascensions and declinations for 230 K-band and 132 Q-band sources. The distribution of K-band sources is illustrated in Fig. 1. Note that: 1) Observations covered down to $\delta \approx -30°$ for sessions 1, 2, 3, and 5. Session 4 went down to $\approx -44°$. 2) Declination uncertainty systematically increases as one moves south. Q-band results are similar but with $\sigma_\delta \approx 1.5$ times larger than at K-band due to lower SNR.

When the minimal 3 coordinates are held fixed in order to set the frame orientation, the solution for the right ascensions and declinations yields median formal K-band position uncertainties of 149 and 290 μas in $\alpha \cos\delta$ and δ, respectively. The solution used 3 hour troposphere breaks and one overall tropospheric gradient per site. The WRMS residuals were 33 ps in delay and 48 fs/s in rate. For Q-band the corresponding position uncertainties were 225 and 392 μas in $\alpha \cos\delta$ and δ, respectively. We have assumed that proper motions and parallaxes are negligible. The MODEST software (Sovers, Fanselow & Jacobs (1998)) was used both for the physical modelling and parameter estimation used to build all the references frames compared in this paper.

4. Internal and External Catalog Comparisons

Experience with S/X data analysis suggests that formal uncertainties may underestimate true errors (*e.g.* Jacobs *et al* (1998), Ma *et al* (1998)). In order estimate the true accuracy of our reference frame, we made two comparisons: K vs. S/X frame and K vs. Q-band.

A recent JPL S/X solution labelled DDOR_2002 (3 million delay measurements, 1978–2002) provides an external standard of comparison. This frame is an unpublished extension of the ICRF extension-1 frame verified to be consistent with that frame at the 100 μas (WRMS) level. For the 156 sources in common which have $\leq$ 2 mas formal uncertainties, the mean in $\Delta\alpha \cos\delta$ was 149 μas and the WRMS about the mean was 333 μas. Both these values are too large to be explained by the modelled formal uncertainties and thus indicate the presence of unmodelled systematic errors. The mean of $\Delta\delta$ was 109 μas and the WRMS about the mean was 586 μas, again, indicating the presence of systematic errors in the declinations. While these comparisons do not determine to what extent the systematic errors are in the K vs. the S/X frame, the latter's vastly larger data set and more carefully scrutinized analyses lends more weight to the S/X results. Thus, our working hypothesis is that K-band systematic errors dominate the comparison.

Turning from external to internal consistency, let's compare the two high frequency frames: K and Q-band. Using data from sessions 1, 2, 3, and 5, there were 118 sources in common which had $\sigma_\delta \leq$ 2 mas. The coordinate differences were consistent with the formal uncertainties as evidenced by median normalized differences in $\Delta\alpha$ and $\Delta\delta$ of 1.1 and 1.0, respectively. The mean K$-$Q differences were, respectively, $< \Delta\alpha\cos\delta > \; = \; 5 \pm 25$ μas and in $< \Delta\delta >= 13 \pm 36$ μas. The WRMS differences about the mean were 267 μas in $\alpha\cos\delta$ and 389 μas in δ.

We take the K-Q normalized differences to be an indication that plasma effects are not yet dominating our error budget. Thermal noise is still an issue especially at Q-band (*cf.* Lanyi et al, 2004). As further data are added, formal uncertainties will decrease thereby making smaller K vs. Q-band systematic effects visible. Thus we are considering various strategies for dealing with and quantifying plasma systematic effects as they arise in future analyses.

5. Geometric Weakness

Because there is evidence for unmodelled systematic errors, we will now take a closer look at possible underlying causes for the differences. Given the small number of sessions, we suspected that the reference frames might suffer from geometric weakness due to the lack of long southern baselines and the lack of variation in the schedules. To explore this we created two K-band solutions. The first had the minimal 3 coordinate parameters fixed. The second had 8 coordinates (from 4 well spread sources) constrained to the S/X solution values in order to control large scale zonal errors and thereby appropriate some of the geometric strength of the S/X solution.

With 3 coordinates constrained, the mean and WRMS agreement in $\alpha\cos\delta$ were 149 and 333 μas, respectively. With 8 coordinates constrained, the mean and WRMS agreement were reduced to 21 and 229 μas, respectively. The declinations also showed improvement when the extra constraints were added. For 3 constraints, the mean and WRMS agreement in δ were 109 and 586 μas, respectively. Imposing 5 additional constraints improved the mean and WRMS agreement in δ to 83 and 433 μas, respectively.

5.1. Right Ascension Inter-Source Correlations

In further searching for the underlying cause of the systematic errors, we discovered that the position parameters themselves were not yet well separated by the data in hand. Figs. 2a. and b. show the right ascension inter-source correlations vs. the arclength between a given pair of sources. On the left, Fig. 2a. reflects the solution with 3 coordinates fixed whereas Fig. 2b., on the right, reflects 8 coordinates held fixed. The most obvious and important change between the two figures is that the additional 5 constraints on the solution leads to large reductions in inter-source correlations.

From these plots we observe that, with our current data set, the right ascensions are significantly positively correlated especially for separations less than about 35°. This leaves the solution vulnerable to systematic changes of the positions of the sources over the sky—i.e. zonal errors. The deficiency appears to worsen as one moves further south in declination, presumably because the northern-based VLBA's observing geometry is systematically weakened for southern observations. We conclude that *a minimally constrained solution is not yet able to separate adequately the position parameters.*

6. Conclusions

We have presented the motivation for and initial results from our program to develop global celestial reference frames at K and Q-bands. At K-band 230 sources have been observed with median formal position uncertainties of $\sigma(\alpha \cos\delta) \approx 150$ μas and $\sigma(\delta) \approx 300$ μas; the corresponding uncertainties for 132 Q-band sources were $\sigma(\alpha \cos\delta) \approx 215$ μas and $\sigma(\delta) \approx 360$ μas. The true accuracy of our results has been estimated from both internal and external comparisons. K and Q-band solutions showed internal agreement at ≈ 270 and ≈ 390 μas in $\alpha \cos\delta$ and δ, respectively. Comparison with the independent and more strongly established S/X frame gave WRMS agreement in the corresponding parameters to 330 and 590 μas, respectively.

Examination of inter-source correlations shows that after 5 sessions we have not yet well separated the estimated position parameters. Perhaps this should not be a surprise given that the S/X work took two decades to get to its present level. We will need a stronger North-South geometry in order to create a more rigid frame that can stand independently of the S/X frame. Thus our work must be continued and refined before any high frequency frame can surpass the S/X frame.

Before we undertook the work described in this paper, there was very little global astrometric data available at frequencies above X-band (8.4 GHz). There were uncertainties as to whether reference frames at K, Q, and Ka-bands were even feasible. The results presented in this paper have answered our questions well enough that we are now optimistic about the future of high frequency radio frames both for general astrometry and spacecraft tracking. We have a reasonably large catalog of reasonably strong sources detected at both K-band (24 GHz) and Q-band (43 GHz) to begin supporting demonstrations of spacecraft measurements in late 2005. In conclusion, this work is a major step forward for both the astrometry and spacecraft navigation communities.

7. Acknowledgements

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References

[1] Ma, C., E.F. Arias, T.M. Eubanks, A.L. Fey, A.-M. Gontier, C.S. Jacobs, O.J. Sovers, B.A. Archinal, and P. Charlot, "The ICRF as Realized by VLBI", AJ, 116, 1, pp. 516-546, July 1998.

[2] Boboltz, D. A., Fey, A. L., P. Charlot, E .B. Fomalont, G. E. Lanyi, L. D. Zhang, & KQ VLBI Survey Collaboration, "Extending ICRF to Higher Radio Frequencies: Imaging & Source Structure," this vol.

[3] Jacobs, C.S., O.J. Sovers, C.J. Naudet, R.F. Coker, and R.P. Branson, "The JPL Extragalactic Ra-

dio Reference Frame: Astrometric Results of 1978-96 Deep Space Network VLBI", NASA JPL TDA Progress Reports, vol. 133, pp. 1-55, 15 May 1998.

[4] Lanyi, G.E., D. Gordon, O.J. Sovers, "Limitations to Dual Frequency Ionospheric Corrections for Frequency Switched K/Q Observations with the VLBA", this volume.

[5] Sovers, O.J., J.L. Fanselow, & C.S. Jacobs, "Astrometry & Geodesy with Radio Interferometry: Experiments, Models, Results", Rev Mod Phys, 70, 4, Oct. 1998.

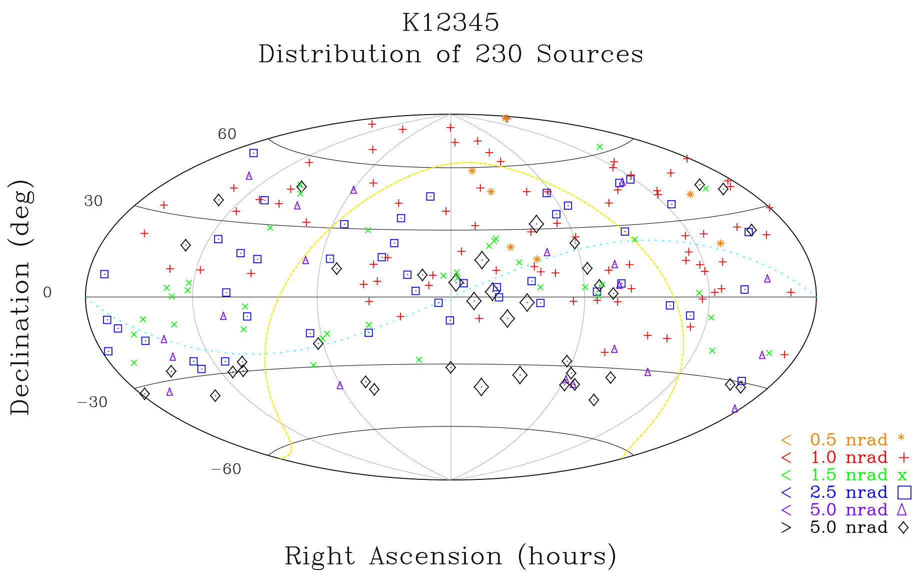
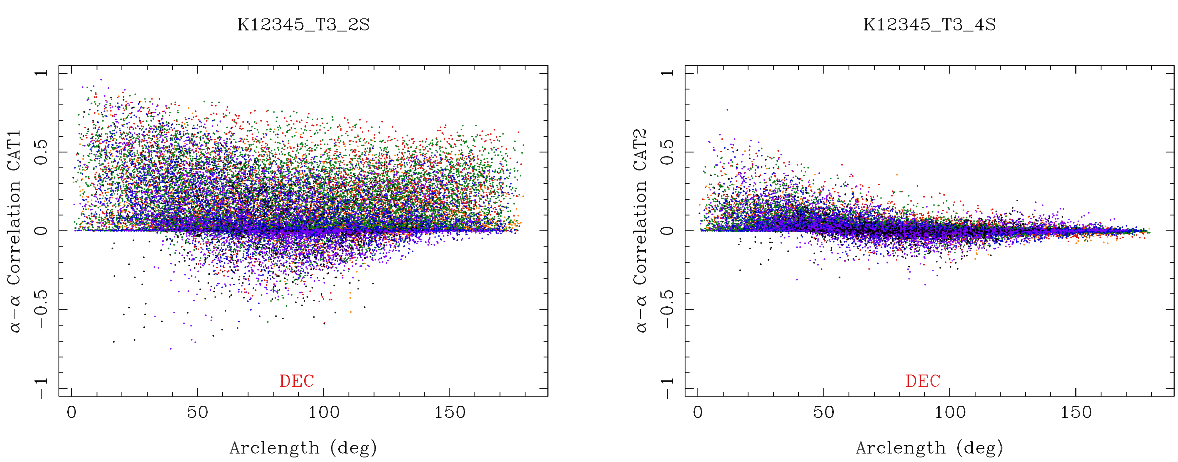


Figure 1. Distribution of the 230 K-band sources. Symbols indicate size of σ_δ.



a. Minimal 3 coordinates constrained.

b. Increase to 8 coordinates constrained.

Figure 2. K-band right ascension inter-source correlations. Note in Fig. b. on the left, how constraining an additional 5 K-band coordinates to their S/X values greatly reduces the correlations.