Highlights of Astronomy, Volume 16
XXVIIIth IAU General Assembly, August 2012
T. Montmerle, ed.

doi:10.1017/S1743921314005468

Celestial reference frames at multiple radio wavelengths

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Abstract. In 1997 the IAU adopted the International Celestial Reference Frame (ICRF) built from S/X VLBI data. In response to IAU resolutions encouraging the extension of the ICRF to additional frequency bands, VLBI frames have been made at 24, 32, and 43 GHz. Meanwhile, the 8.4 GHz work has been greatly improved with the 2009 release of the ICRF-2. This paper discusses the motivations for extending the ICRF to these higher frequency radio bands. Results to date will be summarized including evidence that the high frequency frames are rapidly approaching the accuracy of the 8.4 GHz ICRF-2. We discuss current limiting errors and prospects for the future accuracy of radio reference frames. We note that comparison of multiple radio frames is characterizing the frequency dependent systematic noise floor from extended source morphology and core shift. Finally, given Gaia's potential for high accuracy optical astrometry, we have simulated the precision of a radio-optical frame tie to be ∼10–15 μas (1-σ, per component).

Keywords. astrometry, reference systems, (galaxies:) quasars: general, instrumentation: interferometers, techniques: high angular resolution, radio continuum: galaxies

1. Introduction

The past decade has seen the expansion of global celestial reference frame work from S/X-band (e.g., Ma *et al.*, *AJ*, 1998) to three new frequencies: K-band and Q-band (Lanyi *et al.* AJ, 2010), and X/Ka-band (García-Miró *et al.* IVS, 2012). What changes when moving to these higher radio frequencies? Sensitivity worsens because (1) system temperatures and atmospheric absorption increase due to the H_2O 22 GHz and O_2 60 GHz lines, (2) antenna surface shape control becomes more difficult (3) antenna pointing becomes more difficult as the beam tightens (4) sources become more resolved. However, there is much to be gained. Sources become more compact. There is less extended structure as steep spectrum jet plumes fade (Charlot *et al.* AJ, 2010). Core shift decreases as one goes to higher frequencies (Sokolovsky *et al.* 2011, Kovalev *et al.* 2008, Porcas, *A&A*, 2009). The combined effect is that the astrophysical character of the sources becomes better for astrometry. Given that the sensitivity concerns raised can be solved by recording more bits using ever cheaper digital hard drive technology, moving to higher frequencies is on the whole a very attractive proposition for VLBI radio astrometry.

2. Overview of existing frames

At present, radio frames have been constructed at four frequencies. Their properties are summarized in Table 1. The S/X frame is the most well established. It has the longest history, the most data, and has undergone the most analyses. The current IAU standard celestial frame is the ICRF-2 based on S/X data. The (now dormant) work on K and Q-band frames from the last decade proved that high accuracy frames could be built above 8 GHz. The main limitation of K/Q frames arises from having data only from the

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all-northern VLBA thereby limiting observations to $\delta > -40°$ and allowing $\Delta\delta$ vs. δ zonal errors of 100s of μas. The X/Ka frame has 482 sources well distributed for $\delta > -45°$. While it has no significant $\Delta\delta$ vs. δ zonal error, the precision becomes increasingly worse as one moves southward. X/Ka agreement with the ICRF-2 for 450 common sources is about 200 and 270 μas in $\alpha \cos\delta$ and δ, respectively.

Frame	Frequency (GHz)	wavelength (cm)	Accuracy (μas)	$N_{sources}$	Reference
S/X	2.3/8.4	13/3.6	∼40–100	3414	Ma *et al.* IERS Tech Note 35, 2009
K	24	1.2	∼100	268	Lanyi *et al.* AJ, 139, 5, 2010
Q	43	0.7	∼300	131	Lanyi *et al.* AJ, 139, 5, 2010
X/Ka	8.4/32	3.6/0.9	∼225	482	García-Miró *et al.* IVS, 2012

Table 1. Existing Celestial Reference Frames at Radio Frequencies

3. Future prospects for improvement

Four key aspects of VLBI can potentially be improved by the end of the decade.

(1) SNR: Modern digital recording (Whitney *et al.* IVS 2012) makes it affordable to increase data rates from current operations at 128–448 Mbps up to 2048–16,000 Mbps.

(2) Instrumentation: Digital Back Ends (Ruszczyk *et al.* Tuccari; Garcia-Miro *et al.* all IVS 2012) are replacing obsolete analog systems thereby improving channel uniformity, phase linearity and stability. Better frequency standards ('clocks') are possible (e.g. Petit & Arias, IAU 2012), but appear to be years away from operational use in VLBI.

(3) Troposphere: Many sites are moving to smaller, faster slewing antennas allowing faster sampling of the fluctuating troposphere. Improved Water Vapor Radiometer (WVR) calibrations have been demonstrated (Tanner *et al.* RSci, 2003; Bar-Sever *et al.* IEEE, 2007).

(4) Southern geometry: At S/X, the addition of 3 AuScope antennas plus Warwick, New Zealand creates more southern observing opportunities. At K-band, HART, S. Africa has an un-cooled receiver with yet-to-be-used potential. At X/Ka, the Malargue, Argentina 35-m (online Nov. 2012) gives immediate, significant improvements to network geometry.

4. Frame tie: VLBI radio frames to Gaia optical frame

The Gaia mission (Prusti; Mignard, IAU, 2012) plans (2013 launch) to acquire high accuracy optical astrometry for 10^9 stars including 500,000 quasars (V < 20 mag). Of these, a few thousand are expected to be both optically bright (V < 18 mag) and radio loud (30–300+ mJy) and thus suitable for optical-radio comparisons. Such comparisons will first require that the conventional 3-D orientation of the frames be aligned. Charlot & Bourda (IAU-JD7, 2012) have a strategy for maximizing the number of optically bright (V<18) quasars which are also detectable with S/X-band VLBI. García-Miró *et al.* (IVS, 2012), using existing X/Ka data and projected Gaia errors, estimate a tie precision of ∼10 μas (1-σ) per 3-D component which could improve as more X/Ka data arrives.

Acknowledgements

I would like to acknowledge my colleagues who acquired and analyzed the data—especially the IVS, the ICRF2 working group, the KQ VLBI collaboration, and the X/Ka VLBI collaboration. This research was done in part under contract with NASA. Government sponsorship acknowledged.

https://doi.org/10.1017/S1743921314005468 Published online by Cambridge University Press