# X/Ka VLBI FRAME'S ROLE IN MULTI-WAVELENGTH STUDIES

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ABSTRACT. This paper is an update of Sotuela et al. (2011) which improves their simulated Gaia frame tie precision by ∼10% by adding three additional VLBI observing sessions. Astrometry at X/Ka-band (8.4/32 GHz) using NASAs Deep Space Network has detected 466 quasars with accuracies of 200–300 $\mu$as. A program is underway to reduce errors by a factor of 2–3. From our sample, 345 sources have optical magnitudes $V < 20$ and should also be detectable by Gaia. A covariance study using existing X/Ka data and simulated Gaia uncertainties for the 345 objects yields a frame tie precision of 10–15 $\mu$as (1-$\sigma$). The characterization of wavelength dependent systematics from extended source morphology and core shift should benefit greatly from adding X/Ka-band measurements to S/X-band (2.3/8.4 GHz) measurements thus helping to constrain astrophysical models of the wavelength dependence of positions.

## 1. INTRODUCTION

Our X/Ka celestial frame is best understood in the context of the ICRF2 and the planned Gaia frame. The ICRF2 (Ma et al., 2009) based on 8.4 GHz VLBI observations of 3414 extragalactic radio sources is the current IAU fundamental frame. Its position noise floor is $\sim$40 $\mu$as; $\sim$10 $\mu$as in axes. The Gaia extragalactic optical frame (Lindegren et al., 2008) will be based on $10^9$ objects down to $V = 20$ magnitude with accuracy of 25 $\mu$as at $V = 16$ and $\sim$200 $\mu$as at $V = 20$. The catalog is expected in 2021.

## 2. ALIGNING VLBI AND GAIA FRAMES

Quasars being at great distances ($\sim$Gpc) have no measurable proper motion or parallax making them ideal for both VLBI and Gaia quasi-inertial frames. However, the absolute orientation is poorly constrained. Thus frames are first aligned by estimating a 3-D rotational offset ("frame tie") using common objects before doing multi-wavelength studies such as the relative offsets of optical-radio emissions.

There are challenges in making an accurate frame tie: detecting common objects, uniformity of sky coverage, wavelength dependence of emission centroids, and non-point-like morphology (source structure).

*Detecting common objects*: Most quasars don't produce both strong optical and radio detections. Our X/Ka sources have a median optical magnitude of $V = 18.6$ which is at the weak end of Gaia's detection range. There are few sources which are ideal in both the optical and radio. The Bourda et al. (2011) solution is to seek weaker radio objects which are optically bright (V<18) and compensate by leveraging improvements in ground-based radio detection which allow going to 30 mJy.

*Simulated frame tie precision*: Our current X/Ka data has 345 sources with V<20 including 132 with V<18. X/Ka positions have $\sim$200 $\mu$as precision. Corresponding predicted Gaia precisions are $\sim$100 $\mu$as. A frame tie covariance study using these precisions estimated that 3-D rotational alignment could be determined to $\pm$14, $\pm$11, and $\pm$10 $\mu$as in Rx, Ry, and Rz, respectively (1-$\sigma$). Because radio precision is the limiting factor, anticipated radio improvements have potential to improve the tie to 5–10 $\mu$as by the end of Gaia's mission. However, tie accuracy may be limited not by precision, but by systematic errors.

*Extending uniform sky coverage south*: VLBI has weak coverage in the south due to the small number of southern stations. X/Ka coverage (Figure 1) is weak in the mid-south and totally lacking in the south polar cap. However, simulations (Bourda et al., 2010) show that a very small data set of 1000 delay measurements on a 9000 km "all-southern" baseline could dramatically improve the X/Ka frame.

We have now gone beyond simulation by identifying 498 candidates (Figure 2) which have strong, very compact X-band VLBI detections thus making them excellent candidates for VLBI at Ka-band. In particular, Figure 2, shows numerous well distributed candidates in the south polar cap. Thus prospects for uniform sky coverage at X/Ka-band are very positive with potential for 900+ sources.

*Compactness and core shift*: VLBI frames now exist at 24 and 43 GHz (Lanyi et al., 2010; Charlot et al., 2010), and 32 GHz (Jacobs et al., 2011). These intermediate frequencies between the 8-GHz ICRF2 and Gaia's optical enable frequency dependent systematic error studies: chiefly, extended structure from emissions out in the jet and shifts in the radio core's position. Because we observe mostly blazars which are characterized by jets pointing near the line of sight, we observe down the 'throat' of the jets thus bringing into consideration opacity effects. Higher frequency observations may see farther into the jets thus changing the observed position. However, Porcas (2009) notes that group delay observations such as our X/Ka data may greatly reduce this core shift effect.

On average systematic errors from non-point-like source structure are reduced as extended emissions tend to fade with increasing radio frequency. In our core dominated sources, the radio core position is thought to occur at a point near where the optical depth becomes unity. The frequency dependence of the jet's opacity is suspected to move the core closer to the central engine as frequency increases. Thus moving to higher frequencies may reduce both systematic errors thereby improving the radio-optical tie.

*Outlook*: Our goal is to improve 32-GHz VLBI to the 70 $\mu$as accuracy achieved by the 8-GHz ICRF2 and projected for Gaia ($18^{th}$ mag). Accuracy improvements focus on three items:
1. We have increased our data rate by 4x and expect another 4x. The total 16x improves precision 4x.
2. We are building phase-cal tone generators in order to reduce instrumental errors by a factor of 10.
3. We are seeking improved southern geometry. Simulations (Bourda et al., 2010) show that adding an all-southern baseline from our existing Australian antenna to either S. Africa or S. America allows 200 $\mu$as accuracy over the south polar cap. If we are successful in all three areas, the X/Ka frame has potential for 70 $\mu$as accuracy over the full sky. Thus we would have X/Ka precision comparable to Gaia at $18^{th}$ mag while greatly reducing radio systematic errors from source structure and core shift.

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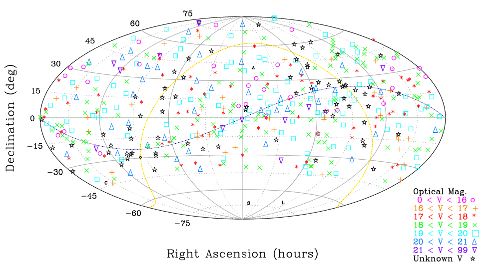


Figure 1: Distribution of 466 X/Ka sources. Optical counterpart $V$ magnitude defined in legend. $(\alpha, \delta) = (0, 0)$ is at the center. The ecliptic is indicated by the sinusoidal curve. The galactic plane is indicated by the $\Omega$-shaped yellow curve. Note the large number of sources lacking optical identifications near the galactic plane, especially near its center and anti-center.

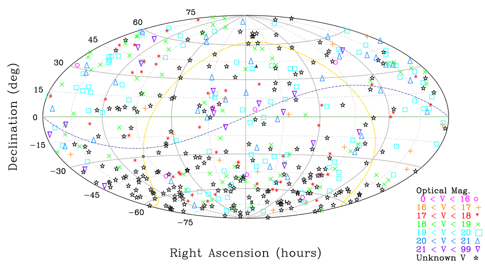


Figure 2: Distribution of 498 X/Ka candidates. Color code is same as Fig. 1. Selection is based on unresolved X-band flux $\geq$ 200 mJy and $\geq$ 70% of the total flux in the unresolved core. [input list: L. Petrov, astrogeo.org, rfc2011a]. South polar cap is well covered, but lacks optical identifications for many candidates. $2^{nd}$ southern station will be needed to observe cap.