The Contribution of X/Ka-band VLBI to Multi-wavelength Celestial Frame Studies

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Abstract: We report the results of VLBI astrometry using NASA's Deep Space Network at X/Ka-band (3.6/0.9, 8.4-32 GHz). We detected 459 quasars with current accuracy of 200-300 μas. The leading components of the error budget have been identified and a program is underway to reduce position errors by a factor of 2. We show that if VLBI data from source structure and core shift. The characterization of wavelength dependent systematic errors from extended source morphology and core shift should greatly benefit from adding X/Ka-band measurements to existing and planned X/S-band measurements thus helping to constrain astrophysical models of the wavelength dependence of photocenter positions.

Background: Celestial reference frames have been used for millennia for navigation and to study the motions of bodies in the heavens. Today the interest is as great as ever as celestial frames are used for many purposes such as to guide spacecraft to the planets and to study the proper motions of stars within the galaxy and beyond.

VLBI extragalactic radio frame

The current International Astronomical Union (IAU) fundamental celestial reference frame is the 2p2 International Celestial Reference Frame (ICRF) (Ma et al. 2009) based on VLBI observations at 3.6 cm of 3414 extragalactic radio sources, including 298 “defining” sources which determine the orientation of the frame's axes. The ICRF has a noise floor of ~40 μas in positions and 10 μas in axis stability.

Gaia extragalactic optical frame

Gaia is an optical mission (2012 launch) planned to survey ~100,000 objects down to V=20 mag with an unprecedented accuracy, ranging from a few tens of mas at V = 15 to 18 to about 200 μas at V = 20 (Lindegren et al. 2008). About 500,000 quasars should be detected with about 20,000 of those objects being optically bright (V=18). We expect perhaps 2,000 of those optical quasars to also be good sources in the radio (30 to 300 mJy). The preliminary Gaia catalog is expected by 2015 with the final version in 2021.

Aligning VLBI and Gaia frames

The quasars are very distant (of order Gpc) and so do not exhibit measurable proper motion or parallax. Both the Gaia frame and the VLBI frame make use of these properties to create a quasi-inertial frame. However, the absolute orientation of the frame is poorly constrained by the physics involved and, in fact, at the milli-arcsec (mas) level orientation is purely a matter of convention. Thus in order to compare the Gaia and VLBI frames one has to force them into the same conventional orientation. This will be done by estimating a 3-D rotation ("frame tie") for the highest quality objects common to both frames. This will allow positions from both systems to be accurately registered and thus enable multi-wavelength studies of objects of interest such as the relative locations of optical and radio emissions within active galactic nuclei. There are a number of challenges to the establishment of an accurate frame tie: Sensitivity, uniformity of sky coverage, wavelength dependence of emission centroids, and non-point-like morphology of the sources (structure source).

1. Sensitivity: Observation of weaker radio sources to optical/galactic brightness counterparts

Not all quasars produce strong detections in both the optical and the radio (Fig. 1). In fact, many optically detectable quasars are not detected in the radio ("radio quiet"). Conversely, the radio detections which we present have a median optical magnitude of V=18.6 which is at the weak end of Gaia's range of detection. So it is difficult to find objects which are ideal in both the optical and radio domains. The solution being pursued by Bourda et al (this meeting) is to seek out weaker radio objects which are optically bright (V<18). This approach leverages the ongoing improvements in ground-based radio detection so as not to change the use of objects as weak as 30 mas in the radio.

1b. Simulated frame tie precision

Our current X/Ka VLBI data has 306 objects with V<20 including 130 bright objects with V<18. The radio positions are known at X/Ka-band with about ~200 μas precision. Simulated position predictions expected from Gaia for these objects is to predict about ~100 μas in the optical. These radio and optical positions were used in a frame tie covariance study which estimated that the 3-D rotational alignment was 1.8 mas rms (25 μas per axis) (Ry and the requirement for data sets). Because this result is limited by the current radio predictions which are expected to continue to improve during the Gaia mission, we expect the tie precision to improve by a factor of 2 or 3 to 5-10 μas by the end of the Gaia mission. While this predicted precision is encouraging there is much work remaining in order to understand the systematic errors which may result by the accuracy, uniformity of sky coverage, wavelength dependence of emission centroids, and non-point-like morphology of the sources (structure source).

2. Uniform sky coverage: the need for improvements in the south

VLBI has historically weak coverage of the southern hemisphere due to the small number of southern VLBI sources. While special experiments have improved the uniformity of coverage in the SX-band based ICRF2, the coverage in our own X/Ka-band results (Fig. 2a) is weak in the mid-south and totally lacking in the south polar cap. We are seeking to correct this weakness. Simulations (Bourda et al., Proc. Sci., Italy, 2006) showed that even a very small data set of 1008 delay measurements on a 8000 km all southern baseline could dramatically improve the X/Ka frame. We have now gone beyond simulation by identifying 498 candidates (Fig. 2b) which have strong (very short) baselines. We thus have a number of candidates for X/KaVLBI at X-band. In particular, Fig. 2b, shows numerous well distributed candidates in the far south. Thus prospects for uniform sky coverage at X/Ka-band are very positive for potential for as many as 900+ sources!

3. Extension to higher radio frequencies to improve source compactness and reduce core shift

VLBI radio frequency has been extended recently to 24 and 43 GHz (Laroy et al., Chetrit et al. 2010), and 32 GHz (Jacobs et al. 2011). By providing these intermediate frequencies between traditional astrometric VLBI at 8 GHz and Gaia at optical frequencies, these new frames are enabling the study of frequency dependent systematic errors: chiefly, extended structure from emissions farther out in the jet and shifts in the radio core's position (Fig. 3). On average systematic errors from non-point-like source structure are reduced as extended emissions tend to fade with increasing radio frequency. In our present context the jet 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 radio frequencies may reduce both of these radio systematic errors thereby improving the radio-optical frame. The challenge is to improve the accuracy of the radio-to-optical frequency measurements to the ~70 μas level achieved by 8 GHz VLBI and projected for Gaia measurements (at 18th mag). The current 32 GHz radio frames of 459 sources (Fig. 3a) has an accuracy of ~200 μas in the North and is a factor of a few worse in the far South. About 1/3 of the 32 GHz sources have an optically-bright (V<18) counterpart suitable for the alignment with the Gaia frame. In order to improve accuracy, we are addressing three items:

3a. Identifying new sources have been sensitivity limited, we have increased our data rate by 4X and expect another 4X within a year. This total 16X will improve precision by a factor of 4.

3b. We are building instrumental phase stabilizers in order to reduce instrumental errors by a factor of 10.

3c. Lastly, we are seeking to improve our instrumental models: Fig. 2b shows candidate sources with an emphasis on the southern polar cap. Simulations (Bourda, Chetrit & Jacobs, 2010) show that adding just a few days of data from a southern baseline from our existing Australian antenna to either S. Africa or S. America allows 200 μas accuracy over the south polar cap.

If we are successful by 2015 in all three areas, the X/Ka-band frame has potential for 70 μas accuracy over the full sky in the time for the Gaia preliminary catalog. Thus we would have a radio frame with precision comparable to Gaia precision for 18th mag quasars with greatly reduced radio systematic errors from source structure and core shift.

Conclusions: The X/Ka-band work presented here is one facet of the multi-wavelength VLBI work now underway. Our X/Ka-band frame has 459 sources with 200-300 μas accuracy. Our work shows that coverage can be made much more uniform much more over the southern sources. Simulations predict that this frame could be tied to the Gaia frame with 10-15 μas precision. Accuracy is likely to be limited by systematic errors which are under study as wavelength dependent errors from extended source morphology and core shift. Thus it is essential to gather data at multiple wavelengths (e.g. SX and X/Ka-bands) in order to characterize the true accuracy of the radio to optical frame.

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Fig. 1. Aligning VLBI and Gaia frames. SOURCES: 2009.

Fig. 2a. 459 radio sources detected at X/Ka-band (8.4/32 GHz). Magnitude of optical counterparts indicated by color code. Note the large number of unknown optical IDs near galactic plane (yellow curve) especially near Galactic center & anti-center. (Jacobs et al. EVA. 2011)

Fig. 2b. 498 candidate sources based on X-band unresolved flux > 200 mJy which is also ~70% of total flux. Note large number of candidates lacking optical IDs in southern polar cap.

Fig. 3. Schematic of quasar (Marscher)