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 (3.6/0.9cm, 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 to 3. More than 300 of our sources should also be detectable by Gaia (V< 20 mag). A covariance study using the existing X/Ka radio data and simulated Gaia uncertainties for the 300+ objects shows that a frame tie could be made with a precision of 10-15 µas (1-sigma) for each of the three rotation parameters with the potential for 5 µas precision if our error budget reduction plan succeeds. The characterization of wavelength dependent systematic errors from extended source morphology and core shift should benefit greatly from adding X/Ka-band measurements to existing and planned S/X-band measurements thus helping to constrain astrophysical models of the wavelength dependence of photocenter positions.

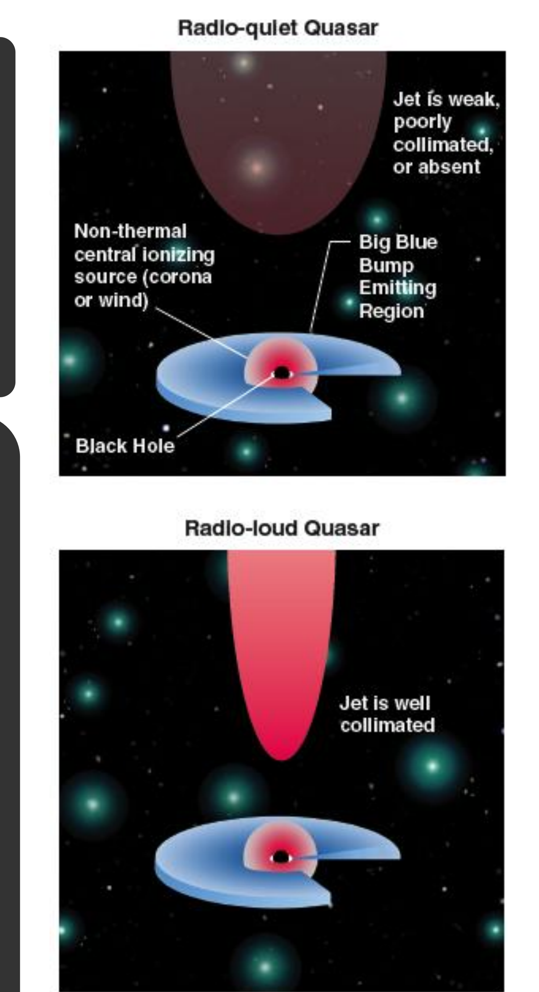

Fig. 1: Wehrle et al, µas Science, Socorro, 2009

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 2nd International Celestial Reference Frame (ICRF2) [Ma et al, 2009] based on VLBI observations at 3.6cm of 3414 extragalactic radio sources, including 295 "defining" sources which determine the orientation of the frame's axes. The ICRF2 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 10^9 objects down to V=20 magnitude, with an unprecedented accuracy, ranging from a few tens of µas 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 these optically bright 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-arsec (mas) level the 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 emissions (source structure).

1a. Sensitivity: *Observation of weaker radio sources to gain optically brighter 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 limits which should allow the use of objects as weak as 30 mJy 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 precisions expected from Gaia for these objects are predicted to be about ~100 µas in the optical. These radio and optical precisions were used in a frame tie covariance study which estimated that the 3-D rotational alignment could be determined to +-16, +-13, and +-11 µas in Rx, Ry, and Rz, respectively (1-sigma). Because this result is limited by the current radio precisions 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 limit the accuracy of the tie. We now turn to those systematic errors.

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

Historically, VLBI has had weak coverage of the southern hemisphere due to the small number of southern VLBI antennas. While special experiments have improved the uniformity of coverage in the S/X-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, Charlot, & Jacobs, 2010] showed that even 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 (Fig. 2b) which have strong, very compact X-band VLBI detections thus making them excellent candidates for VLBI at Ka-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 with potential for as many as 900+ sources!

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., EVGA, 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. [input list: L. Petrov, astrogeo.org, rfc2011a]

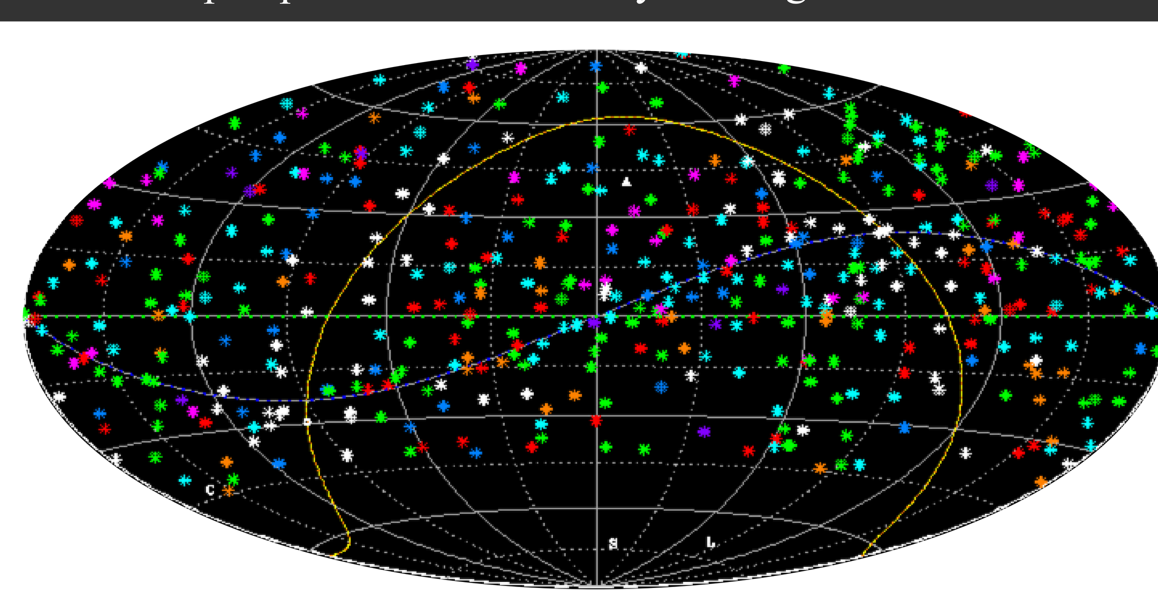

Fig. 2a. X/Ka (3.6/0.9cm, 8.4/32 GHz) Detected 459 sources

Optical magnitude
Magenta 0 < V < 16
Orange 16 < V < 17
Red 17 < V < 18
Green 17 < V < 19
Cyan 19 < V < 20
Blue 20 < V < 21
Purple 21 < V < 99
White Unknown

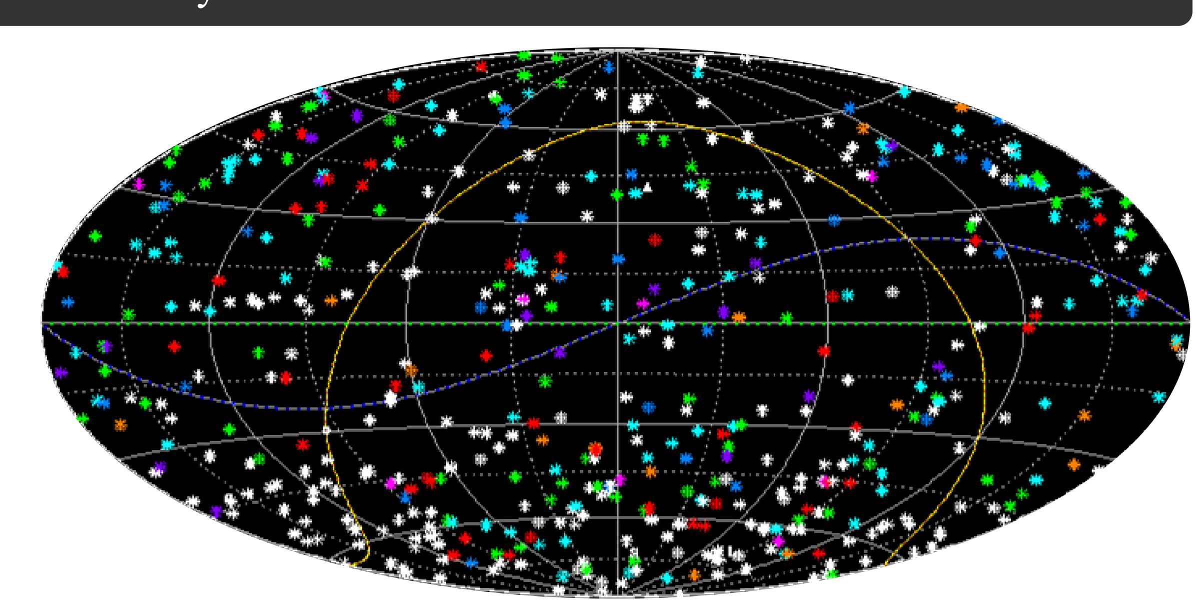

Fig. 2b. 498 Candidate Ka-band sources. (Note south cap)

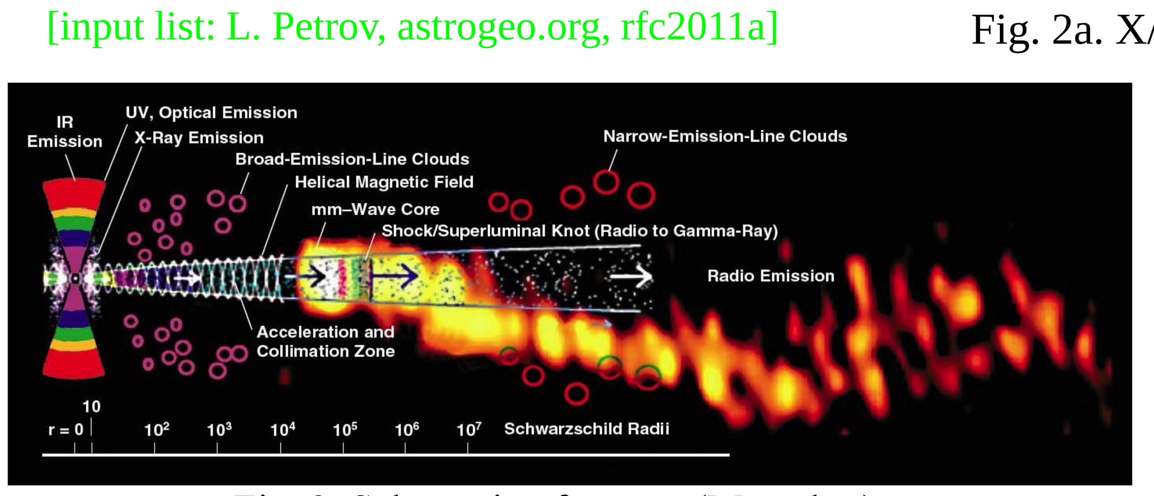

Fig. 3. Schematic of quasar (Marscher)

Fig. 3: Schematic of quasar. [Fig. Credit: Marscher, Proc. Sci., Italy, 2006. Krichbaum et al, IRAM, 1999. Wehrle et al, ASTRO-2010]
Marscher et al. have gone a long way toward confirming the adjacent picture of an active galactic nuclei. Note the x-axis is a logarithmic scale in units of Schwartzchild radii. While the accretion disk radiates in the optical as well as IR, UV and X-ray, The mm to cm regime radio is thought to be created by synchrotron emissions near the shock at the end of an accelerated flow. The question we hope to eventually address with our measurements is to what extent the centroid of radio emissions shifts position as a function of wavelength --the so-called "core-shift". Because of relativistic beaming the jets we observe tend to be the ones pointed almost directly towards the earth. This selection effect means that the observer tends to be looking down the "throat" of the jets thus bringing into consideration opacity effects: higher frequency observations may see farther down into the jets thus changing the observed position of the emission. However, Porcas [AA, 505, 2009] notes that group delay observations such as our X/Ka data may greatly reduce this core shift effect.

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

VLBI radio frame work has been extended recently to 24 and 43 GHz [Lanyi et al., Charlot 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 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 radio frequencies may reduce both of these radio systematic errors thereby improving the radio-optical frame tie.

The challenge is to improve the accuracy of high frequency radio measurements to the ~70 µas level achieved by 8 GHz VLBI and projected for Gaia measurements (at 18th mag). The current 32 GHz radio frame of 459 sources (Fig. 2a) 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:

* Because existing measurements 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.
* We are building instrumental phase calibrators in order to reduce instrumental errors by a factor of 10.
* Lastly, we are seeking to improve our southern geometry. Fig. 2b shows candidate sources with an emphasis on the southern polar cap. Simulations [Bourda, Charlot ,& 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 especially in the south. 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 such as wavelength dependent errors from extended source morphology and core shift. Thus it is essential to gather data at multiple wavelengths (e.g. S/X and X/Ka-bands) in order to characterize the true accuracy of the radio to optical frame tie.

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