PROCEEDINGS OF SCIENCE

A VLBI survey of weak extragalactic radio sources to align the ICRF and the future Gaia celestial reference frame

G. Bourda* **and P. Charlot**
Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, CNRS UMR 5804
BP89, 33271 Floirac Cedex, France
E-mail: bourda@obs.u-bordeaux1.fr

R. Porcas

Max-Planck-Institute for Radio Astronomy, P.O. Box 2024, 53010 Bonn, Germany

S. Garrington

Jodrell Bank Observatory, The University of Manchester, Macclesfield, Cheshire, SK11 9DL, UK

The space astrometry mission Gaia will construct a dense optical QSO-based celestial reference frame. For consistency between optical and radio positions, it will be important to align the Gaia reference frame and the International Celestial Reference Frame (ICRF) with the highest accuracy. Currently, it is found that only 10% of the ICRF sources are suitable to establish this link (70 sources), either because they are not bright enough at optical wavelengths or because they have significant extended radio emission which precludes reaching the highest astrometric accuracy. In order to improve the situation, we have initiated a multi-step VLBI survey dedicated to finding additional suitable radio sources for aligning the two frames. The sample consists of about 450 sources, typically 20 times weaker than the current ICRF sources, which have been selected by cross-correlating optical and radio catalogues. This paper presents the observing strategy to detect, image, and measure accurate positions for these sources. It also provides results about their VLBI detectability, as derived from observations with the European VLBI Network in June and October 2007. Based on these observations, an excellent detection rate of 89% is found, which is very promising for the continuation of this project.

The 9th European VLBI Network Symposium on The role of VLBI in the Golden Age for Radio Astronomy and EVN Users Meeting
September 23-26, 2008
Bologna, Italy

*Speaker.

1. Context

The International Celestial Reference Frame (ICRF) is the realization at radio wavelengths of the International Celestial Reference System (ICRS [1]), through Very Long Baseline Interferometry (VLBI) measurements of extragalactic radio source positions [2, 3]. It was adopted by the International Astronomical Union (IAU) as the fundamental celestial reference frame during the IAU 23^{rd} General Assembly at Kyoto (Japan), in 1997. The ICRF currently consists of a catalogue with the VLBI coordinates of 717 extragalactic radio sources (from which 212 are defining sources), with sub-milliarcsecond accuracy.

The European space astrometry mission Gaia, to be launched by 2011, will survey about (i) one billion stars in our Galaxy and throughout the Local Group, and (ii) 500 000 Quasi Stellar Objects (QSOs), down to an apparent optical magnitude V of 20 [4]. Optical positions with Gaia will be determined with an unprecedented accuracy, ranging from a few tens of microarcseconds (μas) at magnitude 15–18 to about 200 μas at magnitude 20 [5]. Unlike Hipparcos, Gaia will permit the realization of the extragalactic reference frame directly at optical bands, based on the QSOs that have the most accurate positions (i.e. those with $V \leq 18$ [6]; it is expected to detect at least 10 000 of such QSOs [7]). A preliminary Gaia catalogue is expected to be available by 2015 with the final version released by 2020.

In the future, aligning the ICRF and the Gaia frame will be crucial for ensuring consistency between the measured radio and optical positions. This alignment, to be determined with the highest accuracy, requires several hundreds of common sources, with a uniform sky coverage and very accurate radio and optical positions. Obtaining such accurate positions implies that the link sources must have (i) an apparent optical magnitude V brighter than 18 (for the highest Gaia astrometric accuracy), and (ii) no extended VLBI structures (for the highest VLBI astrometric accuracy).

In a previous study, we investigated the current status of this alignment based on the present list of ICRF sources [8]. We showed that although about 30% of the ICRF sources have an optical counterpart with $V \leq 18$, only one third of these are compact enough on VLBI scales for the highest astrometric accuracy. Overall only 10% of the current ICRF sources (70 sources) are available today for the alignment with the future Gaia frame. This highlights the need to identify additional suitable radio sources, which is the purpose of the project described here.

2. Strategy to identify new VLBI radio sources for the ICRF–Gaia alignment

Searching for additional radio sources suitable for aligning accurately the ICRF and the Gaia frame could rely on the VLBA Calibrator Survey (VCS [9, 10, 11, 12, 13, 14]), a catalogue of about 3000 extragalactic radio sources observed with the VLBA (Very Long Baseline Array). This investigation is currently underway. Another possibility is to search for new VLBI sources, which implies going to weaker radio sources that have a flux density typically below 100 mJy. This can now be envisioned owing to the recent increase in the VLBI network sensitivity (i.e. recording now possible at 1 Gb/s) and by using a network with big antennas like the EVN (European VLBI Network).

A sample of about 450 radio sources that mostly have never been observed with VLBI (i.e. not part of the ICRF or VCS) has been selected for this purpose by cross-identifying the NRAO VLA

Sky Survey (NVSS [15]), a deep radio survey (complete to the 2.5 mJy level) that covers the entire sky north of -40°, with the Véron-Cetty & Véron (2006) optical catalogue of QSOs [16]. This sample is based on the following criteria: $V \leq 18$ (for an accurate position with Gaia), $\delta \geq -10^\circ$ (for possible observing with northern VLBI arrays), and NVSS flux density $\geq$ 20 mJy (for possible VLBI detection).

The observing strategy to identify the appropriate link sources in the sample includes three successive steps: (1) to determine the VLBI detectability of these weak radio sources, mostly not observed before with VLBI; (2) to image the sources detected in the previous step, in order to reveal their VLBI structure; and (3) to determine an accurate astrometric position for the most point–like sources of the sample.

3. VLBI results

VLBI observations for this project were carried out in June and October 2007 (during two 48–hours experiments, named EC025A and EC025B, respectively), with a network of 4 or 5 VLBI antennas from the EVN (Effelsberg, Medicina, Noto, Onsala; and the 70 m Robledo telescope for part of the time in EC025B). The purpose of these two experiments was to determine the VLBI detectability of the 447 weak radio sources in our sample based on snapshot observations.

In this analysis, a source is considered as detected if it has a SNR $\geq$ 7 on at least one baseline for at least one scan. Therefore, based on 5-minutes on-source integration time, the minimum flux densities that can be detected at S and X bands respectively by the the most sensitive baselines are:

- 9 mJy (S-band) and 2 mJy (X-band), for the baseline Medicina to Effelsberg;
- 2 mJy (S-band) and 0.5 mJy (X-band), for the baseline Robledo to Effelsberg, during EC025B.

Our results indicate excellent detection rates of 97% at X band and 89% at S band. Overall, 398 sources were detected at both frequencies, corresponding to an overall detection rate of about 89% which is in agreement with that reported in Frey et al. (2008) (80% [17]) for quasars from the Sloan Digital Sky Survey. The overall mean correlated flux densities were determined for each source and band by the mean over all scans and baselines detected:

- At X band, 432 sources were detected and the mean correlated fluxes range from 1 mJy to 190 mJy, with a median value of 26 mJy.
- At S band, 399 sources were detected and the mean correlated fluxes range from 8 mJy to 481 mJy, with a median value of 46 mJy.

A comparison between the X-band flux density distribution for our sources, those from the VCS and the ICRF shows that the sources of our sample are indeed much weaker. On average, they are 27 times weaker than the ICRF sources and 8 times weaker than the VCS sources (and even by restricting the comparison to the flux densities lower than 100 mJy, our sources are still 3 times weaker than the VCS sources; see Fig. 1).

The spectral index α ($S \propto \nu^\alpha$, S being the source flux density and ν the frequency) was determined for the 398 radio sources detected at both frequencies (see Fig. 2). The sources with a

PoS(IX EVN Symposium)056

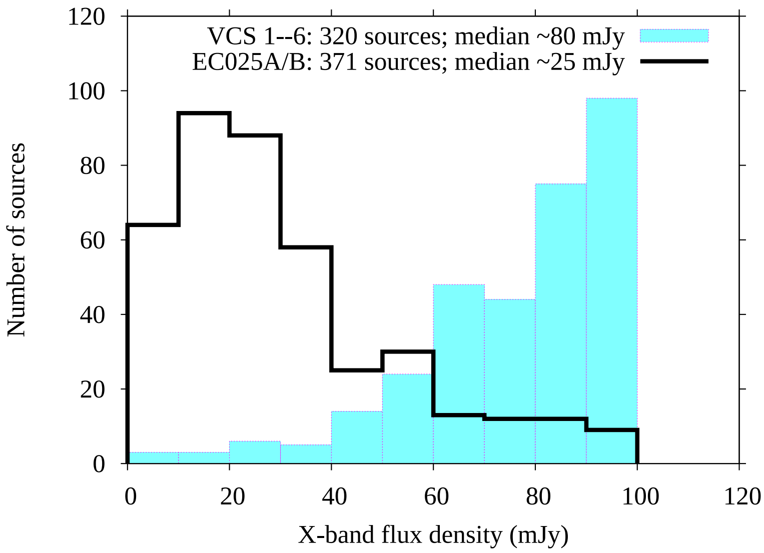

Figure 1: Comparison of the X-band flux density distribution (units in mJy) for the sources detected in our experiments (EC025A and EC025B) and those from the VCS catalogue. The distribution is plotted only for the sources which flux density is smaller than 100 mJy. The corresponding median values for the sources observed in our experiments and those from the VCS catalogue are 25 mJy and 80 mJy , respectively.

compact core are expected to have $\alpha > -0.5$. The corresponding distribution for the sources which also belong to the CLASS catalogue [18], well known to be composed of compact sources, is also plotted and no major differences are noticed. The median value of α in our sample is -0.34 and about 70% of the sources have $\alpha > -0.5$, hence indicating that they must have a dominating core component, which is very promising for the future stages of this project.

4. Summary

Based on observations with the European VLBI Network, we identified 398 new VLBI sources which are potential candidates to align the ICRF and the future Gaia frame. On average, these sources are 27 times weaker than the ICRF sources. Overall, this multiplies by a factor of 6 the current number of potential ICRF–Gaia link sources (pending identification of further candidates from the VCS catalogue).

The excellent detection rate inferred from the observations may suggest that our initial VLBI detection step is unnecessary for such radio sources having an optical counterpart with magnitude brighter than 18.

Future steps will be targeted at imaging the 398 sources that we have detected at both frequencies by using the global VLBI network (EVN+VLBA). This already began with global VLBI observations carried out in March 2008 to image 105 sources from the 398 ones detected. This is aimed at identifying the most point-like sources and therefore the most suitable ones for the ICRF–Gaia link.

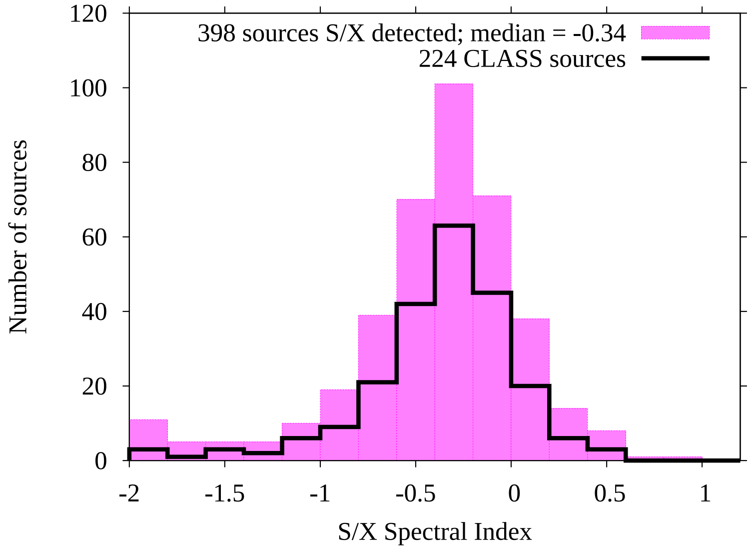

Figure 2: S/X spectral index distribution for the 398 weak extragalactic radio sources detected at both S and X bands during our experiments. Additionally, the S/X spectral index distribution for the sources also belonging to the CLASS catalogue is plotted (in black).

Acknowledgements

The authors wish to thank Dave Graham and Walter Alef for assistance with the correlation in Bonn, John Gipson for advice when scheduling the observations, and Alexander Andrei for providing improved optical positions. This work has benefited from research funding from the European Community's sixth Framework Programme under RadioNet R113CT 2003 5058187. The EVN is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils.

References

[1] E.F. Arias, P. Charlot, M. Feissel & J.-F. Lestrade 1995, *The extragalactic reference system of the International Earth Rotation Service, ICRS*, *A&A* 303, 604

[2] C. Ma, E.F. Arias, T.M. Eubanks, A.L. Fey, A.-M. Gontier, C.S. Jacobs, O.J. Sovers, B.A. Archinal & P. Charlot 1998, *The International Celestial Reference Frame as Realized by Very Long Baseline Interferometry*, *AJ* 116, 516

[3] A.L. Fey, C. Ma, E.F. Arias, P. Charlot, M. Feissel-Vernier, A.-M. Gontier, C.S. Jacobs, J. Li & D.S. MacMillan 2004, *The Second Extension of the International Celestial Reference Frame: ICRF-EXT.1*, *AJ* 127, 3587

[4] M.A.C. Perryman, K.S. de Boer, G. Gilmore, E. Hog, M.G. Lattanzi, L. Lindegren, X. Luri, F. Mignard, O. Pace & P.T. de Zeeuw 2001, *GAIA: Composition, formation and evolution of the Galaxy*, *A&A* 369, 339

[5] L. Lindegren, C. Babusiaux, C. Bailer-Jones, U. Bastian, A.G.A. Brown, M. Cropper, E. Hog, C. Jordi, D. Katz, F. van Leeuwen, X. Luri, F. Mignard, J.H.J. de Bruijne & T. Prusti 2008, *The Gaia*

mission: science, organization and present status, In: A Giant Step: from Milli- to Micro-arcsecond Astrometry, IAU Symposium No. 248 Proceedings, W.J. Wenjin, I. Platais and M.A.C. Perryman (eds.), Cambridge University Press, 217

[6] F. Mignard 2003, *Future Space-Based Celestial Reference Frame*, In: IAU XXV, Joint Discussion 16, R. Gaume, D. McCarthy & J. Souchay (eds.), 133

[7] F. Mignard 2002, *Observations of QSOs and Reference Frame with GAIA*, In: Gaia: A European space project, O. Bienaymé & C. Turon (eds.), EAS Publications series, 2, 327

[8] G. Bourda, P. Charlot & J.-F. Le Campion 2008, *Astrometric suitability of optically-bright ICRF sources for the alignment with the future Gaia celestial reference frame*, *A&A* 490, 403

[9] A.J. Beasley, D. Gordon, A.B. Peck, L. Petrov, D.S. MacMillan, E.B. Fomalont & C. Ma 2002, *The VLBA Calibrator Survey-VCS1*, *ApJS* 141, 13

[10] E.B. Fomalont, L. Petrov, D.S. MacMillan, D. Gordon & C. Ma 2003, *The Second VLBA Calibrator Survey: VCS2*, *AJ* 126, 2562

[11] L. Petrov, Y.Y. Kovalev, E.B. Fomalont & D. Gordon 2005, *The Third VLBA Calibrator Survey: VCS3*, *AJ* 129, 1163

[12] L. Petrov, Y.Y. Kovalev, E.B. Fomalont & D. Gordon 2006, *The Fourth VLBA Calibrator Survey: VCS4*, *AJ* 131, 1872

[13] Y.Y. Kovalev, L. Petrov, E.B. Fomalont & D. Gordon 2007, *The Fifth VLBA Calibrator Survey: VCS5*, *AJ* 133, 1236

[14] L. Petrov, Y.Y. Kovalev, E.B. Fomalont & D. Gordon 2008, *The Sixth VLBA Calibrator Survey: VCS6*, *AJ* 136, 580

[15] J.J. Condon, W.D. Cotton, E.W. Greisen, Q.F. Yin, R.A. Perley, G.B. Taylor & J.J. Broderick 1998, *The NRAO VLA Sky Survey*, *AJ* 115, 1693

[16] M.-P. Véron-Cetty & P. Véron 2006, *A catalogue of quasars and active nuclei: 12th edition*, *A&A* 455, 773

[17] S. Frey, L.I. Gurvits, Z. Paragi, L. Mosoni, M.A. Garrett & S.T. Garrington 2008, *Deep extragalactic VLBI-optical survey (DEVOS). II. Efficient VLBI detection of SDSS quasars*, *A&A* 477, 781

[18] S.T. Myers, N.J. Jackson, I.W.A. Browne, A.G. de Bruyn, T.J. Pearson, A.C.S. Readhead, P.N. Wilkinson, A.D. Biggs, R.D. Blandford, C.D. Fassnacht, L.V.E. Koopmans, D.R. Marlow, J.P. McKean, M.A. Norbury, P.M. Phillips, D. Rusin, M.C. Shepherd & C.M. Sykes 2003, *The Cosmic Lens All-Sky Survey - I. Source selection and observations*, *MNRAS* 341, 1

PoS(IX EVN Symposium)056