TOWARDS A VLBI CATALOG OF OPTICALLY-BRIGHT EXTRAGALACTIC RADIO SOURCES FOR THE ALIGNMENT OF THE RADIO FRAME WITH THE FUTURE GAIA FRAME

G. BOURDA[1], A. COLLIOUD[1], P. CHARLOT[1], R. PORCAS[2], S GARRINGTON[3]
[1] Université de Bordeaux, Observatoire Aquitain des Sciences de l'Univers
CNRS-UMR5804, Laboratoire d'Astrophysique de Bordeaux
2 rue de l'Observatoire, BP 89, F-33271 Floirac Cedex, France
e-mail: bourda@obs.u-bordeaux1.fr

[2] Max-Planck-Institut für Radioastronomie
Auf dem Hügel 69, 53121 Bonn, Germany

[3] University of Manchester, Jodrell Bank Observatory
Macclesfield, Cheshire SK11 9DL, UK

ABSTRACT. 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 and VLBI frames with the highest accuracy. In this respect, it was found that only 70 sources from ICRF were suitable to establish this link, either because they are not bright enough at optical wavelengths or because they show extended radio emission which precludes reaching the highest astrometric accuracy. In order to improve the situation, we initiated a multi-step VLBI observational project, dedicated to finding additional suitable radio sources for aligning the two frames. The sample consists of about 450 optically-bright radio sources, typically 20 times weaker than the ICRF sources, which have been selected by cross-correlating optical and radio catalogs. The initial observations, aimed at checking whether these sources are detectable with VLBI, and conducted with the European VLBI Network in 2007, showed an excellent 90% detection rate. This paper reports on global VLBI observations carried out in March 2008 to image 105 from the 398 previously detected sources. All sources were successfully imaged, revealing point-like VLBI structures for about half of them, which is very promising for the future. While the remaining ∼300 detected sources from our initial sample will be imaged in the same way, the next step, dedicated to measuring accurately the position of these sources, will be engaged in the near future.

1. CONTEXT

During the past decade, the IAU (International Astronomical Union) fundamental celestial reference frame was the ICRF (International Celestial Reference Frame; Ma et al. 1998, Fey et al. 2004), composed of the VLBI (Very Long Baseline Interferometry) positions of 717 extragalactic radio sources, measured from dual-frequency S/X observations (2.3 and 8.4 GHz). Since 1 January 2010, the IAU fundamental celestial reference frame has been the ICRF2 (IERS Technical Note 35), successor of the ICRF. It includes VLBI coordinates for 3 414 extragalactic radio sources, with a floor in position accuracy of 40 μas and an axis stability of 10 μas.

The European space astrometry mission Gaia, to be launched in 2012, will survey all stars and QSOs (Quasi Stellar Objects) brighter than apparent optical magnitude 20 (Perryman et al. 2001). Optical positions with Gaia will be determined with an unprecedented accuracy, ranging from a few tens of μas at magnitude 15–18 to about 200 μas at magnitude 20 (Lindegren et al. 2008). Unlike Hipparcos, Gaia will permit the realization of the extragalactic celestial reference frame directly at optical bands, based on the QSOs that have the most accurate positions. A preliminary Gaia catalog is expected to be available by 2015 with the final version released by 2020.

In this context, aligning VLBI and Gaia frames 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 be brighter than optical magnitude 18 (Mignard 2003), and must not show extended VLBI structures.

In a previous study, we investigated the potential of the ICRF for this alignment and found that only 70 sources (10% of the catalog) are appropriate for this purpose (Bourda et al. 2008). This highlights the need to identify additional suitable radio sources, which is the goal of a VLBI program that we initiated four years ago (Bourda et al. 2010a). This program has been devised to observe 447 optically-bright extragalactic radio sources extracted from the NRAO VLA Sky Survey, a dense catalog of weak radio sources (Condon et al. 1998). The observing strategy to detect, image, and measure accurate VLBI positions for these sources is described in Bourda et al. (2010a).

The initial observations, whose goal was to assess the VLBI detectability of the targets, were conducted with the European VLBI Network (EVN) in 2007. These showed an excellent 90% detection rate (Bourda et al. 2010a). Proceeding further with our program, we now report on global VLBI imaging observations carried out in March 2008 to image 105 of the 398 previously detected sources.

2. OBSERVATIONS AND DATA REDUCTION

The observations were performed during a 48-hour experiment (hereafter designated as GC030), on 7–9 March 2008, with a global VLBI array recording at 512 Mb/s in a dual-frequency S/X mode. This network was composed of 5 telescopes from the EVN (Effelsberg, Medicina, Noto, Onsala-20m and Hartebeesthoek), the DSN 70-m Robledo telescope for part of the time, and 9 antennas of the VLBA (Very Long Baseline Array). Sixteen 8 MHz-wide sub-bands were recorded, with 8 contiguous bands at each of S- and X-band. On average, a total of three to four 5-minute long scans were scheduled on each of the 105 target sources. In addition, we observed a sample of 10 well distributed ICRF sources, for use as calibrators. In all, about 80% of the allocated time was spent on source, while the rest was used for slewing.

The correlation of GC030 was done with the VLBA correlator at the Array Operations Center in Socorro (New Mexico, USA). The correlated data were then calibrated using the Astronomical Image Processing System (AIPS[1]). An initial amplitude calibration for each sub-band was accomplished using system temperature measurements taken during the observations combined with gain curves supplied for each telescope. Prior to fringing the targets, phase offsets between the sub-bands were determined by fringing a short calibrator scan, and then applied to all data. This allowed us to combine all sub-bands together when fringing, thereby increasing the signal-to-noise-ratio and maximizing chances of detection for these weak targets. Calibrators were used in a second stage to estimate amplitude correction factors for each station, each band (S and X), and each sub-band. These corrections, at the level of less than 10% on average, were applied to the calibrated data, which were then exported as FITS files.

The remaining data reduction was conducted with the Caltech DIFMAP[2] software-package which was used for imaging. Visibility data for each frequency band were selfcalibrated, Fourier inverted, and CLEANed following the hybrid-mapping technique (Pearson & Readhead 1984), using DIFMAP in an automatic mode. A point-source model was used as a starting model for the iterative procedure in all cases. Uniform weighting and, after several iterations, natural weighting, were applied to derive the final images.

3. RESULTS

Based on the analysis described above, VLBI maps at X- and S-bands were successfully produced for each of the 105 target sources observed during GC030. These images have the following characteristics:

- The typical beam has a size of about 1.2 × 0.5 mas at X-band and 4.2 × 2.0 mas at S-band.
- The dynamic range (defined as the ratio of the first plotted contour level to the peak brightness) is generally ∼1:100.
- The typical image noise rms is 0.080 mJy/beam at X-band and 0.117 mJy/ beam at S-band. This compares well with the theoretical image thermal noise at X- and S-bands, which are 0.050 and 0.082 mJy/beam, respectively.

When considering all 105 targets, the total flux density ranges from 23 mJy to 222 mJy at X-band, with a median value of 61 mJy, and from 22 mJy to 397 mJy at S-band with a median value of 65 mJy. Based on the X-band and S-band flux densities, the spectral index α (defined as $S \propto \nu^{\alpha}$, where S is the source flux density and ν is the frequency) has also been determined. In this definition, the sources with a

---

[1] http://www.aips.nrao.edu

[2] http://www.astro.caltech.edu/∼tjp/citvlb/index.html

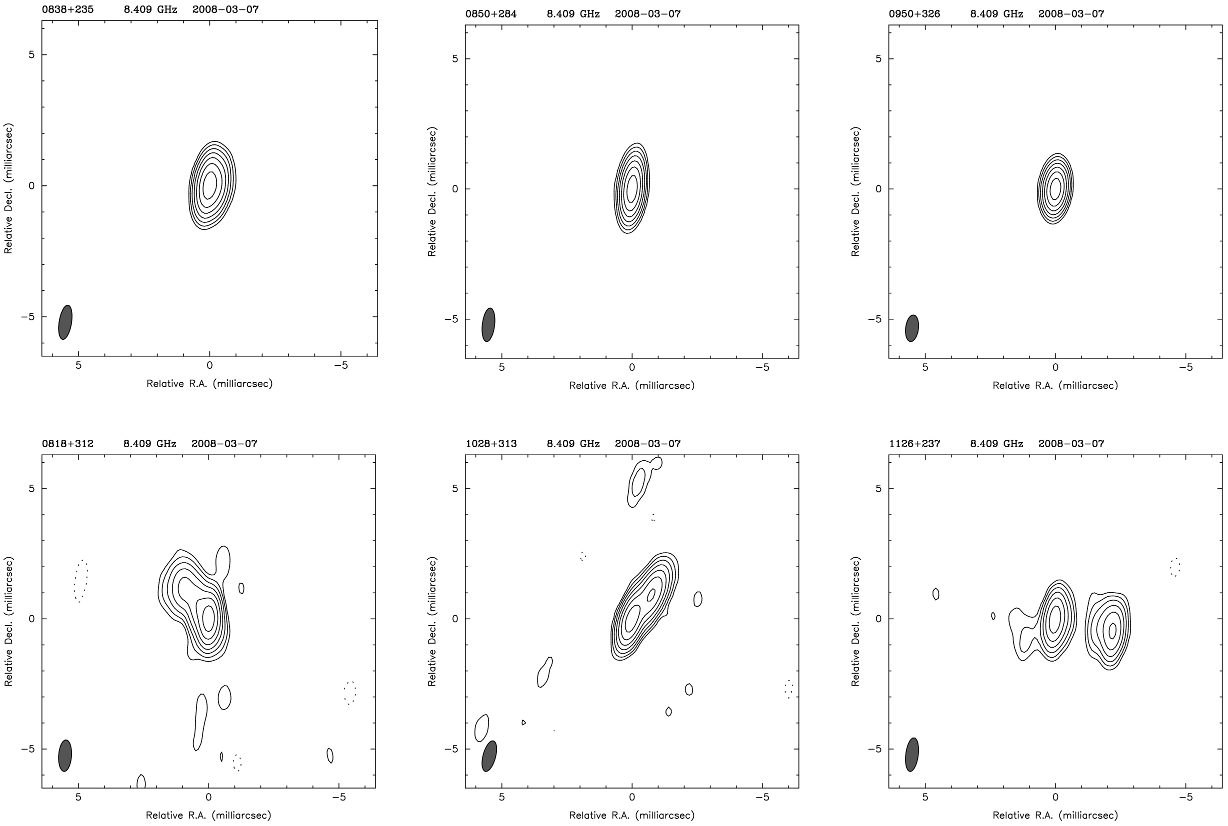

Figure 1: Examples of X-band VLBI maps for sources observed during GC030. *Upper panel*: Three sources suitable for the alignment with Gaia (point-like sources): 0838+235, 0850+284, 0950+326. *Lower panel*: Three sources not suitable for this alignment (sources with extended VLBI structures): 0818+312, 1028+313, 1126+237. The first contour level is typically 1% of the peak brightness, with successive contours increasing by a factor of 2. The FWHM (Full Width at Half Maximum) Gaussian restoring beam applied to the images is shown as an ellipse in the lower left of each panel.

dominating compact core are expected to have $\alpha > -0.5$. The median value of α for the sources observed during GC030 is -0.05, with $\alpha > -0.5$ for more than 90% of the targets (97 sources out of 105 sources imaged).

The images derived from GC030 show a variety of morphologies, ranging from point-like sources to extended or even double sources (e.g. see Fig. 1). In order to identify the most point-like ones, suitable for the Gaia link, we used the so-called "structure index" (SI) as an indicator of astrometric quality (Fey & Charlot 1997; Fey & Charlot 2000). Accordingly, only sources with SI < 3.0 should be used, since one wants to determine the link with the highest accuracy.

Analysis of the structure index values at X- and S-bands for all 105 sources observed during GC030 indicates that about half of them (47 sources) show point-like or compact structures at X-band (SI < 3.0), whereas the other half show extended structures. The resulting list of suitable sources is given in Bourda et al. (2010b) and can be accessed online[3].

4. FUTURE PROSPECTS

From now on, 50% of the remaining 293 detected sources from our initial sample have been observed in 2010, and the 25% still remaining will be observed in March 2011. These sources will be imaged in the same way. Assuming similar statistics, we expect another 150 suitable link sources to be identified. The final stage of this project, dedicated to measuring accurately the VLBI position of those sources, will be

---

[3] http://www.obs.u-bordeaux1.fr/BVID/GC030

engaged during the year 2011. While making the Gaia link possible, these new VLBI positions will also serve in the future to densify the VLBI frame at the same time.

Acknowledgements. The authors would like to thank the VLBI friends at the EVN and VLBA observing stations. 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. The VLBA is part of the National Radio Astronomy Observatory (NRAO), which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

5. REFERENCES

Bourda, G., Charlot, C., Le Campion, J.-F., 2008, "Astrometric suitability of optically-bright ICRF sources for the alignment with the future Gaia celestial reference frame", A&A 490, pp. 403–408.

Bourda, G., Charlot, P., Porcas, R., Garrington, S., 2010a, "VLBI observations of optically-bright extragalactic radio sources for the alignment of the radio frame with the future Gaia frame. I. Source detection", A&A 520, A113.

Bourda, G., Collioud, A., Charlot, P., Porcas, R., Garrington, S., 2010b, "VLBI observations of optically-bright extragalactic radio sources for the alignment of the radio frame with the future Gaia frame. II. Imaging candidate sources", A&A (online).

Condon, J., Cotton, W., Greisen, E., Yin, Q., Perley, R., et al., 1998, "The NRAO VLA Sky Survey", AJ 115, pp. 1693–1716.

Fey, A., Charlot, P., 1997, "VLBA Observations of Radio Reference Frame Sources. II. Astrometric Suitability Based on Observed Structure", ApJS 111, pp. 95–142.

Fey, A., Charlot, P., 2000, "VLBA Observations of Radio Reference Frame Sources. III. Astrometric Suitability of an Additional 225 Sources", ApJS 128, pp. 17–83.

Fey, A., Ma, C., Arias, E., Charlot, P., Feissel-Vernier, M., et al., 2004, "The Second Extension of the International Celestial Reference Frame: ICRF-EXT.1", AJ 127, pp. 3587–3608.

IERS Technical Note 35, 2009, "The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry", A. Fey, D. Gordon & C. Jacobs (eds.), Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie.

Lindegren, L., Babusiaux, C., Bailer-Jones, C., Bastian, U., Brown, A., et al., 2008, "The Gaia mission: science, organization and present status", In: Proceedings of IAU Symposium 248, "A Giant Step: from Milli- to Micro-arcsecond Astrometry", W. Wenjin, I. Platais & M. Perryman (eds.), Cambridge University Press, pp. 217–223.

Ma, C., Arias, E., Eubanks, T., Fey, A., Gontier, A.-M., et al., 1998, "The International Celestial Reference Frame as Realized by Very Long Baseline Interferometry", AJ 116, pp. 516–546.

Mignard, F., 2003, "Future Space-Based Celestial Reference Frame", In: Proceedings of IAU General Assembly XXV, Joint Discussion 16: "The International Celestial Reference System: Maintenance and Future Realization", R. Gaume, D. McCarthy & J. Souchay (eds.), pp. 133–140.

Pearson, T., Readhead, A., 1984, "Image Formation by Self-Calibration in Radio Astronomy", ARA&A 22, pp. 97–130.

Perryman, M., de Boer, K., Gilmore, G., Hog, E., Lattanzi, M., et al., 2001, "GAIA: Composition, formation and evolution of the Galaxy", A&A 369, pp. 339–363.