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CELESTIAL REFERENCE FRAMES IN THE GAIA ERA

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Abstract. A working meeting about Gaia and celestial reference frames, funded by the French AS-Gaia, took place in Bordeaux in October 2008. Researchers from Paris, Nice and Bordeaux observatories met in order to lay the foundations of future studies and collaborations in this field. The fundamental celestial reference system is materialized by the International Celestial Reference Frame (ICRF), based on the VLBI (Very Long Baseline Interferometry) position of extragalactic radio sources with sub-milliarcsecond accuracy. On the basis of at least 10 000 Quasi Stellar Objects (QSOs), Gaia will permit to create its own celestial reference frame by 2015–2020, with an unprecedented positional accuracy (ranging from a few tens of microarcseconds (μas) at magnitude 15–18 to about 200 μas at magnitude 20). For consistency between optical and radio positions, it will be important in the future to align these two frames (the Gaia reference frame and the ICRF) with the highest accuracy. This alignment will be important not only for guaranteeing the proper transition if moving from the radio domain to the optical domain, but also for registering the radio and optical images of any celestial target with the highest accuracy. In this paper, we present the context and the goals of this meeting, review the work carried out in each of the three observatories, and present the outcome of the meeting as well as prospects for the future.

1 Introduction

The French "Action Spécifique Gaia" (AS-Gaia) allocated in 2008 a financial support for organizing a working meeting about the International Celestial Reference Frame (ICRF) and the future extragalactic celestial reference frame from Gaia, as proposed by Patrick Charlot. This workshop took place in Bordeaux Observatory, on 24 October 2008, with 13 participants from three different institutes in France: Laboratoire d'Astrophysique de Bordeaux (LAB – Bordeaux), Observatoire de la Côte d'Azur (OCA – Nice), and SYstèmes de Référence Temps-Espace (SYRTE – Paris). The goal of this meeting was to present the work carried out in each laboratory in the framework of the celestial reference frame for Gaia, in order to coordinate the activities at the national level and generate potential collaborations. Accordingly, several relevant scientific topics were examined in the light of the most recent studies (e.g. the celestial reference frame in the optical and radio domains, the astrometric observations of quasars, or the determination and simulation of catalogs of QSOs). In this paper, we report about this meeting and introduce briefly the research activities presented and discussions that took place during this workshop (for more details see http://www.obs.u-bordeaux1.fr/m2a/meeting/meeting_gaiasrqso).

2 Context

The ICRF is the realization at radio wavelengths of the International Celestial Reference System (ICRS; Arias et al. 1995), through Very Long Baseline Interferometry (VLBI) measurements of extragalactic radio source positions (Ma et al. 1998; Fey et al. 2004). During the International Astronomical Union (IAU) 27$^{\rm th}$ General Assembly at Rio de Janeiro (Brazil), in August 2009, the ICRF2 was adopted as the new fundamental celestial reference frame (see http://www.iers.org/documents/publications/tn/tn35/tn35.pdf). The ICRF2 currently consists of a catalog with the VLBI coordinates of 3414 extragalactic radio sources (from which 295 are defining sources), including the VLBA Calibrator Survey (VCS; see Petrov et al. 2008 and references therein), with sub-milliarcsecond accuracy. It has a noise floor of only 40 μas and an axis stability of 10 μas.

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The ESA space astrometric mission Gaia, to be launched beginning 2012, will survey all stars and QSOs brighter than the 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 several hundreds of μas at magnitude 20 (Lindegren et al. 2008). Based on current estimates from local surveys, it is anticipated that 500 000 such QSOs should be detected. Of these, only the objects with the most accurate positions (e.g. with magnitude brighter than 18) will be used to define the frame. Simulations show that the residual spin of the Gaia frame could be determined to 0.5 μas/yr with a "clean sample" of about 10 000 sources (Mignard 2002). A preliminary Gaia catalog 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 an apparent optical magnitude brighter than 18 (for the highest Gaia astrometric accuracy), and no extended VLBI structures (for the highest VLBI astrometric accuracy). This work is identified as the Gaia work package GWP-S-335-15000 "Alignment to ICRF source list" within the Gaia Data Processing and Analysis Consortium (DPAC).

3 Scientific domains involved

3.1 The celestial reference frame with Gaia

François Mignard (OCA) reviewed the process for determining the Gaia celestial reference frame, which eventually may be based on the optical positions of about 20 000 QSOs (if the criterion "magnitude brighter than 18" is kept). This frame will be at first entirely independent from the ICRF (i.e. with an arbitrary origin and rotating with respect to ICRF), and various steps will have to be completed in order to obtain a frame with no global rotation. The CU8 (Coordination Unit 8: "Catalogue Access") procedure to recognize quasar emission based on photometric information was presented. This will lead to the separation of QSOs from stars or galaxies within the Gaia data. Additional activities relevant to the determination of the Gaia frame will be necessary in the future and have already begun (e.g. simulation of catalogs of QSOs, construction of initial catalog of QSOs for Gaia, alignment with the ICRF). Furthermore, the various possible transverse motions the QSOs may suffer from have been identified (e.g. microlensing, matter ejection, superluminous motion, variable galactic aberration, macrolensing, accelerated motion in the local group), hence leading to an estimate of the accuracy that the Gaia frame should achieve of the order of 0.5–0.3 μas/yr for the residual spin, based on a sample of 50 000–20 000 QSOs.

Jean-Christophe Mauduit (OCA) presented the simulations carried out to create a realistic photometric and spectroscopic catalog of QSOs (i.e. good position distribution, fully representative of photometric and redshift distributions, and synthetic spectra) in the framework of CU2 (Coordination Unit 2: "Data Simulations"), on the basis of a complete Universe model and previous photometric investigations (Slezak & Mignard 2007). A primary spectro-photometric catalog considering the AGN variability has been completed, but discriminating between the various types of quasars (i.e. AGN, QSOs, Seyfert, BL Lac) from spectro-photometric information seems highly challenging for the future.

Jean Souchay (SYRTE) presented the Large Quasar Astrometric Catalog (LQAC; Souchay et al. 2008), which is a compiled catalog of QSOs based on the most reliable optical and radio information available in the literature (e.g. optimized positions, u b v g r i z photometry, redshift, flux densities in several radio bands, and absolute magnitude). This catalog is meant to improve over the catalog of Véron & Véron (2006), where several heterogeneities remain. It is also the basis for constructing the Initial Catalog of QSOs for Gaia (the Large Quasar Reference Frame, LQRF), which is a specific task Alexandre Andrei (Brazil – SYRTE) is responsible for within the DPAC of Gaia (CU3; Coordination Unit 3: "Core Processing"). This catalog should help classifying the Gaia data (Andrei et al. 2009).

3.2 Ground-based optical observations of QSOs, prior to the launch of Gaia

Sébastien Bouquillon (SYRTE–Paris Observatory) presented the current optical astrometric projects, relevant to the Gaia mission, for which observations are planned in the near future. Their purpose is to study: (1) the link between the variations of the magnitude and the photocentre of a quasar, (2) the relation between radio and optical positions of quasars, and (3) the influence of the host galaxy on the photocentre of a quasar. Apart from observing the WMAP satellite (which has similar characteristics as the future Gaia satellite) in preparation of the Gaia mission, thinking of supplementing the observations of Gaia, they plan to observe QSOs down to magnitude 25.

Patrick Charlot presented the optical observations carried out with the meridian instrument at Bordeaux Observatory, which contribute to studying the AGN short and long-term variability. About 50 objects are regularly monitored and for some of them the data base is more than 10 years long.

3.3 Aligning Gaia and VLBI celestial reference frames

François Mignard presented the theoretical basis to establish an accurate alignment within the next 10 years between the two extragalactic celestial reference frames, Gaia (optical) and ICRF (VLBI), in order to ensure continuity between these frames. To establish this alignment, one must define the pole and the origin of the Gaia frame, and then on the basis of a sample of common sources, the best fit between the two frames has to be determined by estimating three rotations. Typically, the accuracy of $\sim$80 μas could be achieved with $\sim$100 sources brighter than magnitude 20. A problem still remains unresolved with the optical-radio core shift (i.e. physically different optical and radio positions), which should induce an additional random noise. On one hand, one can think of solving this issue by averaging and finally removing this effect with the use of several link sources, but on the other hand, this information can be of high interest for astrophysical purposes. As mentioned by Patrick Charlot, a recent study by Kovalev et al. (2008) showed that on average the optical-radio core shift between VLBI and Gaia positions might be of the order of 100 μas (on the basis of a sample of 29 sources, from which they extracted the core-shift between S and X radio bands), which is not negligible at all regarding the anticipated accuracy of the Gaia and VLBI frames by 2015-2020.

Finally, it was shown that only 10% of the current ICRF sources (70 sources) are suitable for the alignment with the future Gaia frame (Bourda et al. 2008), which highlights the need to identify further link sources. We are now extending this study to the ICRF2, which also comprises the VCS surveys (as mentioned above). From the 2197 VCS sources within ICRF2, we found that 2108 have an identified optical counterpart, but only 208 sources are brighter than magnitude 18. We expect to identify another 50–100 sources suitable for the Gaia link. From these studies, it is already clear, however, that one will have to go to weaker flux level to come up ultimately with several hundreds of appropriate Gaia-ICRF link sources. This is the reason why we initiated a multi-step VLBI observational project to observe a sample of 447 sources selected from the NVSS catalog (NRAO VLA Sky Survey; Condon et al. 1998). This project, aimed at finding new VLBI sources suitable for the alignment with the future Gaia frame, will be carried out in three steps, in collaboration with the Max Planck Institute for Radio Astronomy (Bonn, Germany) and the Jodrell Bank Observatory (Manchester, UK). About 90% of the sources (398 sources) were detected in the initial step, conducted during two 48-hours experiments with the EVN (European VLBI Network) in June and October 2007, showing promising results for the future stages of this project (i.e. the mapping of the sources detected and the determination of the astrometric positions for the most point-like of these). The second stage of this project began in March 2008, with global VLBI observations (EVN+VLBA; Very Long Baseline Array) of 105 sources from those detected in step 1. About half of these were found to be point-like (Figure 1), hence indicating that they are suitable for the Gaia alignment. A proposal for observing the rest of the sources detected (293 sources) was submitted to complete the imaging of all the sample. Subsequent astrometric observations are expected to be completed within the next two years.

4 Conclusion

Several actions are conducted within the Gaia community in France in order to prepare for the determination of the Gaia frame as well as to align it with the ICRF or its successor by 2015–2020. The working meeting reported in this paper, financed by the French “Action Spécifique Gaia”, was found to be very fruitful, generating many discussions. It was suggested that another such meeting be organized again (in 2010 ?). The idea of an international meeting in the framework of the Gaia DPAC astrometric community (CU3/CU8) was also mentioned as a possibility.

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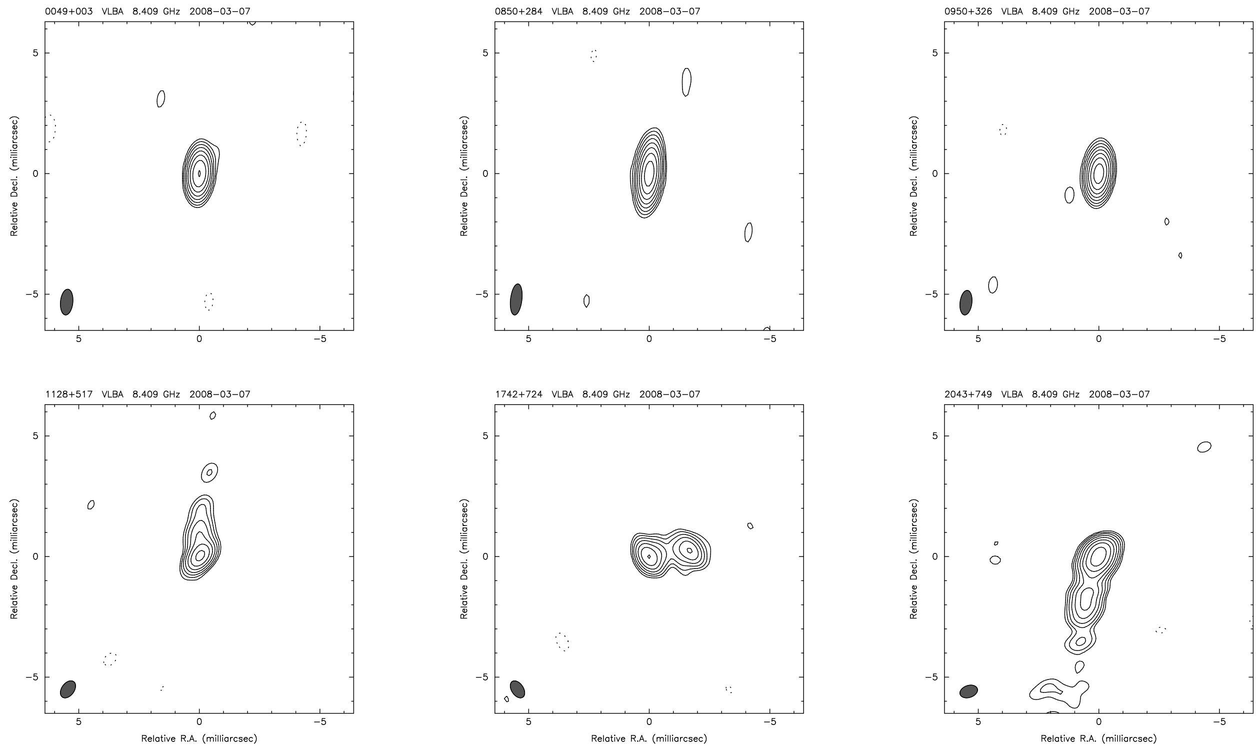

Fig. 1. Examples of VLBI maps (at X band), produced at Bordeaux Observatory, for sources observed during the first global experiment mentioned above (in March 2008). Upper panel: Sources suitable for the ICRF-Gaia alignment (i.e. point-like sources). Lower panel: Sources that are not suitable for the ICRF-Gaia alignment (i.e. sources with extended VLBI structures).

allowed us to organize this working meeting.

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