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The ICRF now and in the future

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Abstract. The current realization of the International Celestial Reference Frame - the ICRF2, in use since January 1, 2010 - includes positions for a total of 3414 extragalactic sources with a noise floor of 40 μas in the individual source coordinates. The ICRF2 positions were determined from measurements acquired at 8.4 and 2.3 GHz with Very Long Baseline Interferometry (VLBI) over the past 30 years. The frame is constantly improving through joint observational efforts of the VLBI community and by taking advantage of the latest refinements in modeling and data acquisition technology, all of which aim at a denser and more accurate celestial frame. Specific work is targeted towards finding the most compact sources, identifying those that are also bright at optical wavelengths and extending the frame at higher radio frequencies. This paper reviews progress in these areas and draws prospects for aligning the VLBI frame with the future Gaia optical frame in the next decade.

Key words. Reference systems – Quasars: general – Techniques: interferometric

1. Introduction

Since the advent of radio interferometry on intercontinental baselines in the 1970's, millions of observations using this technique – usually referred to as Very Long Baseline Interferometry (VLBI) – have been conducted. Such observations yield absolute positions of radio sources with sub-milliarcsecond accuracy. Over the years, accumulated VLBI measurements allowed the community to build an extragalactic reference frame with unprecedented accuracy. Its first realization, the International Celestial Reference Frame (ICRF), was adopted as the fundamental IAU celestial frame in 1997, replacing the old stellar FK5 stellar system (Ma et al. 1998).

The ICRF was based on the radio positions of 608 extragalactic sources estimated from VLBI data acquired at 8.4 and 2.3 GHz between 1979 and 1995 (Ma et al. 1998). Individual ICRF source coordinates had a noise floor of 250 microarcseconds (μas), while the axes of the frame were good to 20 μas. An additional 109 sources was added to the frame a few years later (Fey et al. 2004).

In 2006, the IAU decided to engage the realization of the successor of the ICRF. The motivation for generating this new celestial frame was to benefit from improvements in VLBI modeling and to take advantage of the wealth of VLBI data that had been acquired since the time the ICRF was built. This lead to the ICRF2, which replaced the ICRF on 1 January 2010, after adoption at the XXVII IAU General Assembly in August 2009 (IERS 2010).

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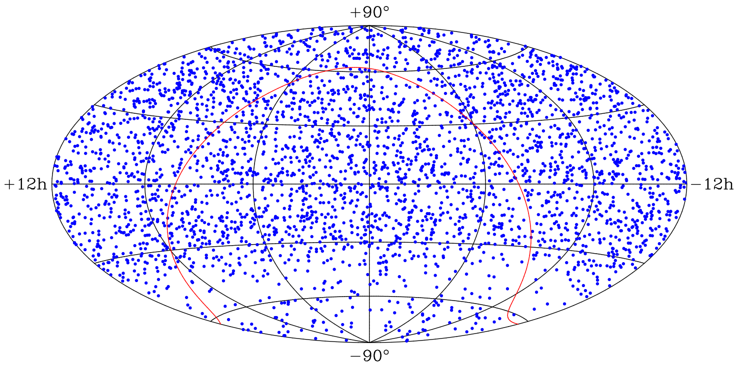

Fig. 1. Distribution of the 3414 ICRF2 sources on the celestial sphere (IERS 2010). The red line represents the Galactic equator.

The next section provides details on the ICRF2, including configuration of data, positional accuracy and the strategy applied to select defining sources. It also reviews ongoing work to extend the frame at higher radio frequencies. Section 3 discusses upgrades of the VLBI observing system. Sections 4 and 5 address issues in aligning the ICRF and the future Gaia optical frame along with the corresponding VLBI observational plans, while Section 6 draws prospects for the long term.

2. The current VLBI reference frame

The most recent realization of the VLBI frame, the ICRF2, was generated from nearly 30 years of VLBI data accumulated during 4540 VLBI sessions conducted at 8.4 and 2.3 GHz between 1979 and 2009 (IERS 2010). Most of these sessions were organized in the framework of the International VLBI Service for geodesy and astrometry (IVS). A small subset of them also comes from dedicated surveys such as the Very Long Baseline Array (VLBA) Calibrator Survey (Beasley et al. 2002; Fomalont et al. 2003; Petrov et al. 2005, 2006; Kovalev et al. 2007; Petrov et al. 2008). In all, 6.5 million VLBI measurements were used to construct the ICRF2. The catalog contains positions for 3414 sources, more than 5 times the number of sources comprised in the ICRF (Fig. 1). The ICRF2 has a noise floor of 40 μas in the individual source coordinates, some 5–6 times better than the ICRF, and an axis stability of 10 μas, twice as stable as the ICRF.

The selection of defining sources for the ICRF2, i.e. those sources that define the axes of the frame, was based on positional stability, source structure and sky distribution (IERS 2010). Fig. 2 shows the positional stability for two sources, 1749+096, which was selected as an ICRF2-defining source, and 0202+149, which falls into the non-defining source category. In Fig. 3, the VLBI morphology of these two sources is shown. The two figures reveal that 1749+096 has a high positional stability and compact structure, as expected for a defining source, whereas 0202+149 has large positional instabilities and extended structure. In all, these two criteria (positional stability and source structure) along with consideration of the source distribution on the sky led to the identification of 295 defining sources among the 3414 sources comprised in the ICRF2.

The VLBI reference frame is improving continuously through joint observational efforts of the VLBI community and by taking advantage of the latest refinements in modeling (e.g. troposphere). A specific effort is also targeted towards extending the frame to higher radio frequencies, chiefly at 24 and 43 GHz (Lanyi et al. 2010; Charlot et al. 2010) and 32 GHz (Jacobs et al. 2011). Measuring source positions at these higher frequencies enables the study of frequency-dependent positional errors which may originate from ex-

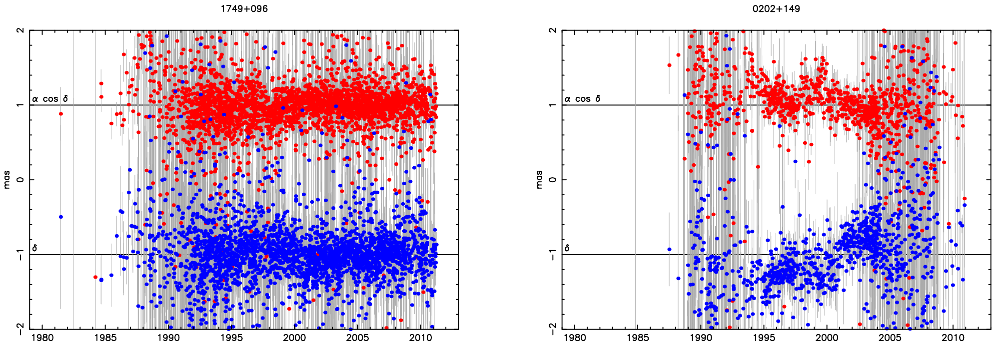

Fig. 2. Positional stability over the past 20 years for two ICRF2 sources: the defining source 1749+096 (left panel) and the non-defining source 0202+149 (right panel). The upper plots are for right ascension and the lower ones for declination. The analysis is from Gontier et al. (2006).

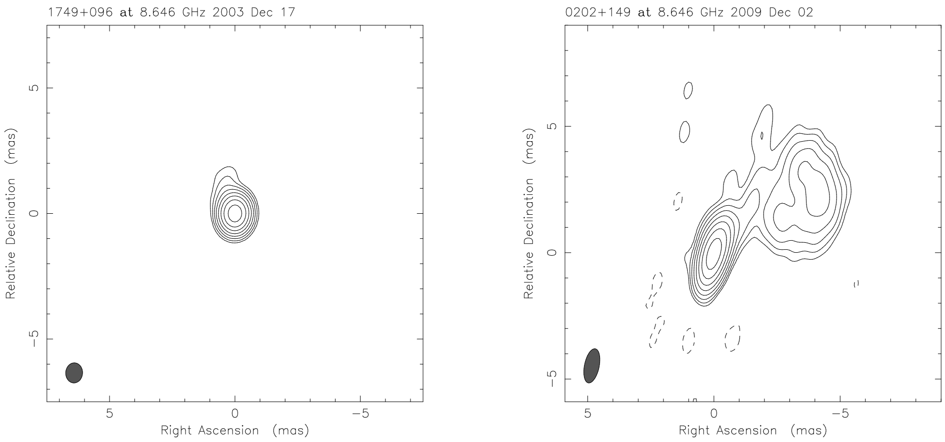

Fig. 3. VLBI morphology at 8.4 GHz for two ICRF2 sources: the defining source 1749+096 (left panel) and the non-defining source 0202+149 (right panel). Contour levels start at 0.5% of the peak brightness. These images are from the Bordeaux VLBI Image Database (BVID) which may be accessed at http://www.obs.u-bordeaux1.fr/BVID/.

tended emission farther out in the source jet and from shifts in the radio core (Charlot 1990; Porcas 2009). Generally, one expects systematic errors from non-point-like source structure to be reduced at higher frequency since extended jet emission tends to fade with increasing radio frequency (Charlot et al. 2010). Current results show that the high-frequency positions agree with the standard 8.4 GHz ICRF2 positions at the 300 μas level, thereby indicating that the frequency-dependent positional shifts are on average below this level.

3. Upgrading the VLBI observing system

The VLBI technique has been constantly improving since its inception more than 40 years ago. During the past decade, major upgrades were conducted in four areas: (i) the construction of new bigger antennas such as that in Yebes (Spain) or others in Russia and China, all in the 30–50 m diameter range, (ii) the replacement of old magnetic tapes by hard disks of ever increasing capacity, (iii) the increase of the recording rates up to 1 Gb/s, and (iv) the development of real-time correlation by transmission of the signal from the telescopes to the correlator over optical fibre networks (e-VLBI). Such upgrades will continue in the coming years, e.g. two new antennas of the 60 m class are being built in Sardinia and in China, while recording rates of 4 Gb/s are now being considered. All these upgrades contribute to increasing the VLBI sensitivity and will facilitate observations of weaker sources, a necessary step towards a further densification of the VLBI celestial reference frame.

On the geodesy side, the IVS community is moving towards a new generation system based on the use of small (12 m diameter) fast-slewing (6–12°/s) automated antennas (Petrachenko et al. 2009). In this new system, the entire frequency range from 2 to 14 GHz is recorded to compensate for the small size of the antennas. For most of the ICRF sources, the required signal-to-noise ratio will be reached within 10 s. In all, the combination of short integration times and reduced source switching times will augment the volume of VLBI data acquired every day by one to two orders of magnitudes compared to the present system, thereby increasing the overall accuracy of the technique. While primarily designed for geodesy and Earth's rotation monitoring, this new system will also make possible re-observation of a large portion of the ICRF everyday, hence contributing to increasing its accuracy and stability. At present, about ten such next generation antennas are being built around the world, while a number of proposals for further sites are in various stages of preparation and approval (Petrachenko et al. 2010).

4. Aligning the VLBI frame and the future Gaia frame

The future realization of a highly-accurate extragalactic reference frame at optical wavelengths by the Gaia space astrometric mission raises the issue of the alignment of this frame with the ICRF2 (or its successor by the time the Gaia frame is built). Such alignment, to be obtained with the highest accuracy, requires a large number of sources common to the two frames, i.e. radio-loud objects with positions accurately known from both VLBI and Gaia. As noted in Mignard (2003), this implies that the sources must be brighter than magnitude 18 (so that their Gaia positions may be derived with the highest accuracy). Additionally, they should have compact VLBI structures on milliarcsecond scales (for highly-accurate VLBI positions). Based on these considerations, a study revealed that only 10% of the ICRF (70 sources) meet these criteria (Bourda et al. 2008), which prompted the development of a specific VLBI observing program dedicated to finding and characterizing additional such suitable sources (Bourda et al. 2010, 2011).

The situation was recently reexamined, taking advantage of the realization of the ICRF2. On a first stage, the ICRF2 was cross-correlated with the Large Quasar Astrometric Catalogue (LQAC) of Souchay et al. (2009). From this comparison, a total of 1128 ICRF2 sources with a proper optical counterpart (i.e. with magnitude *V* or *R* or *I* brighter than 18) was identified. In a second stage, the structure index of these sources, when available, was examined in order to assess their astrometric suitability. In all, 201 sources were found to be compact enough (i.e with a structure index less than 3) to qualify for the alignment (Fig. 4). The distribution of the flux density for these sources is shown in Fig. 5. Compared to the previous ICRF-based identification, this triples the number of suitable sources. However, an additional 100 such sources are still to find to equal the number of ICRF2-defining sources (i.e. 295 sources). Reaching this number is desirable in order to maintain the accuracy of the ICRF2 axes in the case that the IAU fundamental celestial frame is moved to the optical domain when the Gaia catalog is available. In this regard, it is expected that the dedicated VLBI observing program of Bourda et al. (2010) will provide the additional sources required for the alignment.

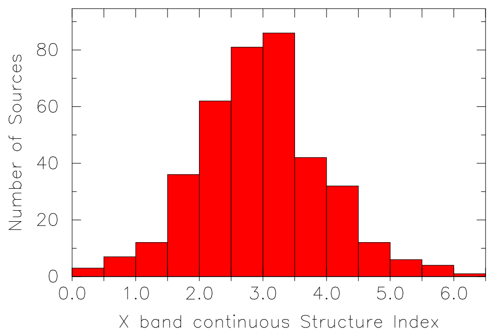

Fig. 4. Distribution of the 8.4 GHz structure index for the ICRF2 sources that have an optical counterpart brighter than magnitude 18 in the LQAC and with a structure index available. Sources with a structure index less than 3 are suitable for the alignment with the Gaia frame.

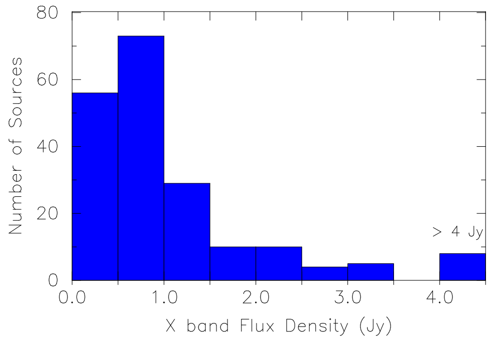

Fig. 5. Distribution of the 8.4 GHz flux density for the 201 ICRF2 sources that meet our criteria for the alignment with the Gaia frame.

5. VLBI observational plans for Gaia

Based on the current list of sources candidate for the alignment, plans are being devised for VLBI observations prior the launch and during the mission. As noted above, highly accurate VLBI positions ($\leq$ 100 μas) are desirable for these sources. This requires measuring positions that are not yet known accurately enough before the launch. For this purpose, specific VLBI astrometric observations will be planned from 2012. Additionally, the sources need to be monitored during the mission in order to control their position stability and accuracy, as well as to detect potential variations in their VLBI structures. To this end, one should take advantage of the Gaia scanning law to schedule simultaneous VLBI and Gaia observations. Besides the alignment between the two frames, such observations should also be of high interest for core shifts studies (Kovalev et al. 2008).

In order to achieve these plans, several VLBI networks may be considered, depending on their specificities. The IVS network may be used for the stronger sources, while the VLBA, EVN (European VLBI Network) and DSN (Deep Space Network) would be used for the weaker sources. The AT-LBA (Australian Telescope – Long Baseline Array) is also necessary for observing sources that are in the far south. Finally, one may consider higher frequency observations (Lanyi et al. 2010; Charlot et al. 2010; Jacobs et al. 2011). The higher the radio frequency, the closer one gets from the base of the radio jet and thus from the optical emission region, hence reducing core-shift effects. Overall, all such observations, prior and during the Gaia mission, should concur to get a very accurate alignment between the VLBI and Gaia frames, which will be highly relevant for astrophysical studies.

6. The long term

At present, the VLBI frame, as materialized by the ICRF2, comprises a few thousands sources, which is less than 1% of the number of extragalactic objects to be detected by Gaia. Despite ongoing upgrades of the technique, it is unlikely that future VLBI frames in this decade be able to compete with the Gaia one in terms of source density – even though the current VLBI astrometric accuracy is now approaching that of Gaia – as it would require sensitivities and resources that are out of reach of existing or foreseen VLBI networks. On the other hand, the Square Kilometer Array (SKA)[1] with its nanoJy extreme sensitivity and survey capability might be able to scan the sky in the same way as Gaia and hence build the radio counterpart of the Gaia optical frame when it comes into operations beyond 2020.

[1] See http://www.skatelescope.org/.

To this end, SKA must have long baselines ($\geq$ 5000 km) and be able to reach an observing frequency of 10 GHz at least, as otherwise the astrometric accuracy will not be sufficient. With such prospects in mind, the VLBI community should start developing innovative observing schemes to use SKA for astrometry. For example, one can think of observing several targets simultaneously with different subarrays to reduce tropospheric errors or using a small subset of SKA to monitor the Earth's rotation permanently, without impacting the science conducted at the same time on the rest of the array, but other ideas are welcome as well.

7. Conclusion

The newly-adopted IAU celestial reference frame, the ICRF2, in use since 1 January 2010, has been a big step forward compared to the original ICRF, both in terms of source density and positional accuracy. Upgrades of the current VLBI networks toward higher sensitivities, higher frequency observations and automation will continue during this decade and will concur to obtaining a denser and even more accurate radio frame in the future. At the same time, the Gaia space astrometric mission will provide the first-ever extragalactic reference frame at optical wavelengths, hence revolutionizing optical astrometry. Two highly-accurate reference frames will thus cohabit and it will be essential to align them at best. To this end, VLBI observational programs have been initiated. The aim is to identify appropriate suitable sources and to measure their astrometric position accurately. Plans are also being made to monitor these sources during the Gaia mission in order to control their positions and further enhance the quality of the alignment. Thanks to this alignment, positions of celestial objects whether extragalactic or galactic will be measured for the first time with a few tens of microarcsecond accuracy at both optical and radio wavelengths. Comparison of the positions will probe directly the geometry and physics of the targets as never done before, which holds promises for new discoveries.

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