Future radio reference frames and implications for the Gaia link

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The celestial reference frame in context

The celestial reference frame is crucial and commonly used in the fields of astronomy and astrophysics for a number of applications: e.g. spacecraft navigation in the solar system, proper motion studies within the Galaxy and the Local Group, or multi-wavelength studies to constrain astrophysical models of celestial objects.

VLBI extragalactic radio reference frame

Since January 1, 2010, the International Astronomical Union (IAU) fundamental celestial reference frame has been the ICRF2 (2nd International Celestial Reference Frame [1]). It consists of a catalog with the Very Long Baseline Interferometry (VLBI) coordinates of 3414 extragalactic radio sources, including 295 "sources of definition" dedicated to determine the orientation of the frame. The corresponding measurements consist of geodetic dual-frequency VLBI observations at 2.3 and 8.4 GHz (i.e. S- and X-band, respectively). This catalog has a noise floor in position of about 60 µas and an axis stability of 10 µas. This frame is constantly improving through joint efforts of the VLBI community.

Gaia extragalactic optical reference frame

The European space astrometry mission Gaia, to be launched in 2012, will survey the whole sky up to magnitude 20, with an unprecedented accuracy, ranging from a few tens of µas at magnitude 15−18 to about 200 µas at magnitude 20 [2]. Based on current estimates from local surveys, it is anticipated that 500 000 Quasi Stellar Objects (QSOs) should be detected, with a large amount of them never observed before. Unlike Hipparcos, Gaia will create its own extragalactic celestial reference frame, directly in the optical domain. This frame will be determined based on the QSOs that will have the most accurate positions with Gaia (e.g. those with magnitude brighter than 18, as suggested by [3]). Simulations show that the residual spin of the Gaia frame could be determined to 0.5 µas/yr with a sample of 10 000 suitable QSOs [4]. A preliminary Gaia catalog is expected to be available by 2015 with the final version released by 2020.

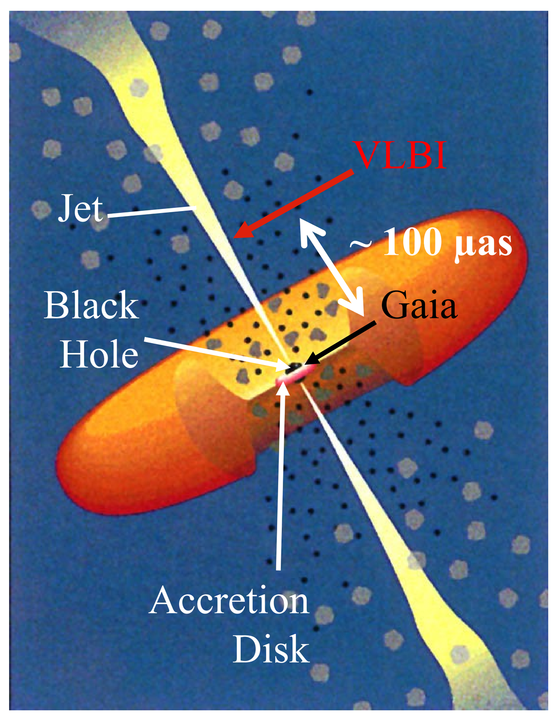


Figure 1: The VLBI radio position in the jet may be offset from the Gaia optical position (nearer to the central "engine") by a shift reaching ~100 µas [5]. Figure modified from C. Urry & P. Padovani (1995).

Aligning VLBI and Gaia frames in the future

Alignment will be crucial for ensuring consistency between the measured radio and optical positions. Comparing these positions will allow one e.g. to pinpoint the relative location of the optical and radio emission in active galactic nuclei (AGN) to a few tens of µas (Fig. 1), placing constraints on the overall AGN geometry. Recent estimates of this optical-radio core shift indicate that it amounts to 100 µas on average [5]. It may thus be directly measurable for a portion of sources. Conversely, these shifts will also affect the accuracy of the link between the two frames. Thus, a large number of objects is desirable in order to average out such effects. Additionally, this alignment, to be determined with the highest accuracy, requires sources with very accurate radio and optical positions. This implies that the link sources must be optically-bright (brighter than magnitude 18, as mentioned above) and not show any extended VLBI structures in order to ensure the highest VLBI astrometric accuracy [6]. Ultimately, the sources devoted to aligning VLBI and Gaia frames should be distributed uniformly on the sky, in order to avoid any systematic effects.

Improving further the radio frame: towards an accurate Gaia link

As mentioned above, the VLBI extragalactic celestial reference frame is improving continuously, by taking advantage of the latest refinements concerning modeling (e.g. troposphere models) and data acquisition technology (e.g. higher recording rates). In this paper, we focus on observational approaches to improve the VLBI frame in the future. These include extension to weaker sources for densification, extension to higher radio frequencies to take advantage of the more compact morphology of the sources at these frequencies, and further observations in the southern hemisphere for more homogeneous sky coverage. Accordingly, we elaborate on how such future radio frames should contribute to aligning precisely the VLBI and Gaia frames within the next decade.

1. Observation of weaker radio sources in order to gain optically-bright counterparts

The VLBI extragalactic celestial reference frame can be improved by densification with radio sources of high astrometric quality. In theory, this could be realized by going to weaker radio sources than usually observed, which are supposed to be more compact (i.e. with a better astrometric quality). With the upcoming Gaia frame, we investigated the potential for alignment of the ICRF sources [7]. This study showed that only 70 ICRF sources (10% of the catalog) were appropriate for this purpose (i.e. V≤18 and point-like VLBI structure). This highlighted the need to identify additional suitable radio sources. Searching for such new sources implies going to weaker flux densities, thereby requiring the use of sensitive VLBI networks such as the European VLBI Network (EVN).

To this end, a VLBI observing project targeting **447 optically-bright weak extragalactic radio sources** has been devised, consisting of three successive steps [8, 9]:

(1) VLBI detection: This step is dedicated to assess the VLBI detectability of these sources.
→ About 90% of the sources were successfully detected [8].

(2) VLBI imaging: This second step is aimed at imaging the sources previously detected, in order to reveal their VLBI structure and to identify the most compact ones.
→ All 105 sources that have been observed so far (out of 398 detected) were imaged successfully, with half of them showing point-like structures on VLBI scales [9] (Fig. 2). *Additional imaging experiments are planned in 2010.*

(3) VLBI astrometry: This final stage will be devoted to determine accurate VLBI positions (<100 µas) for the most point-like sources of the sample (those identified in step 2). *We will engage these astrometric observations by the end of 2010−beginning 2011.*

Because of observing limitations, all targets for this project were located north of −10º declination. For an homogeneous sky coverage, when determining the link, **similar observations should also be undertaken in the southern hemisphere**. Ultimately, both the northern- and southern-hemisphere link sources will be of high interest for densifying the VLBI frame, in addition to permitting an accurate link between the radio and optical frames.

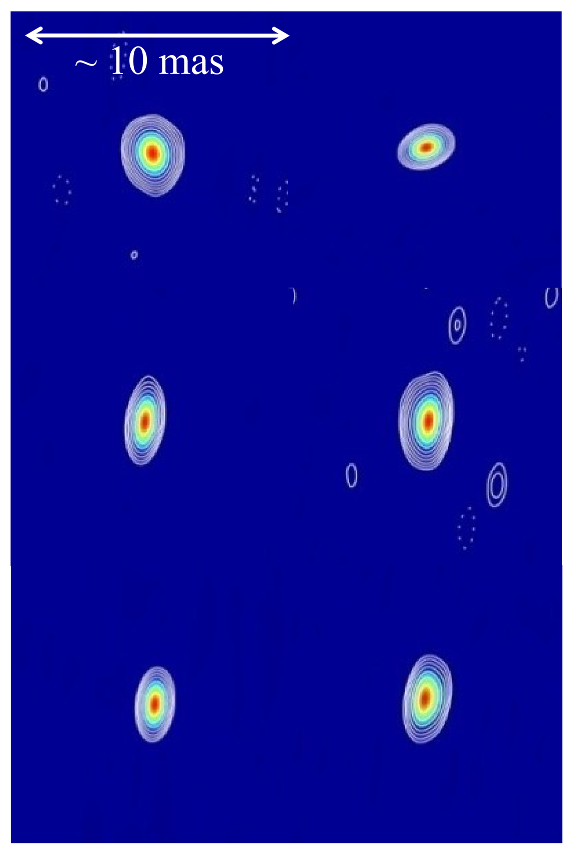
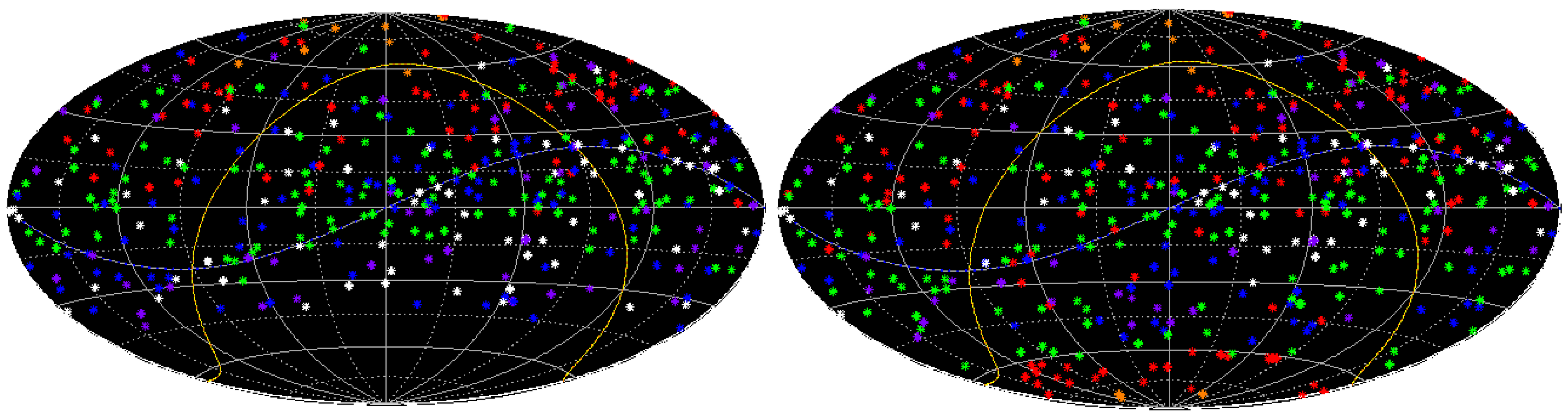


Figure 2: A sample of VLBI images at X-band (8.4 GHz) for six radio sources candidates for the Gaia link [9]. The images show point-like radio emission, indicating that the sources are suitable for the link.

Figure 3: **a.** Sky distribution of the radio sources already observed for the construction of the X/Ka frame (8.4/32 GHz) [12].
b. Sky distribution augmented with simulated additional baseline in the southern hemisphere (~9000 km baseline: Australia to South America or South Africa). Just 1000 delay measurements yield a huge improvement both in terms of sky coverage and the precision of the frame especially in the south.

Declination Sigma	
Orange	< 100 µas
Red	< 200 µas
Green	< 300 µas
Blue	< 500 µas
Purple	< 1000 µas
White	> 1000 µas

a. Existing 32 GHz data **b. Add Simulated Southern data**



2. 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 [10, 11], and 32 GHz [12]. 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. 1). 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 415 sources (Fig. 3a) has an accuracy of ~200 µas in the North and is a factor of a few worse in the far South. About half 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 are in the process of increasing our data rate by a factor of 10 which will improve precision by a factor of ~3.
* 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. Figure 3b shows the simulated benefit of adding just a few days of data from a southern baseline from our existing Australian antenna to either S. Africa or S. America.

If we are successful by 2015 in all three areas, the 32 GHz 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.

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