THE BRIGHT REFERENCE FRAME OF GAIA AND VLBI OBSERVATIONS OF RADIO STARS

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ABSTRACT. The *Gaia* Celestial Reference Frame is defined by faint quasars, and it is assumed that the positions and proper motions of other sources are expressed in the same frame. For *Gaia* DR2, position differences for Hipparcos stars at epoch J1991.25 show that the proper motion system of the bright ($G < 13$) sources in DR2 rotate by about 0.15 mas yr^{-1}. This is confirmed by Lindegren (2020), using a new algorithm to compare DR2 data with published VLBI astrometry for 41 radio stars. The spin of the bright reference frame of *Gaia* DR2 is caused by the different modes of observation in *Gaia* and related calibration issues unresolved in DR2. To validate the bright reference frame of *Gaia* in future data releases will require accurate positional VLBI observations to be acquired in the next 5–10 years for the largest possible set of suitable radio stars.

1. THE GAIA CELESTIAL REFERENCE FRAME

The second release of *Gaia* data (DR2; Gaia Collaboration et al., 2018a) provides full astrometric information (positions, parallaxes, and proper motions) for 1331 million sources at the reference epoch J2015.5. Their magnitudes in the integrated *Gaia* band range from $G \simeq 3$ to 21, although the astrometry is unreliable for $G \lesssim 6$ due to detector saturation. The positions and proper motions of all sources are formally given in the second realisation of the *Gaia* Celestial Reference Frame, *Gaia*-CRF2 (Gaia Collaboration et al., 2018b).

The primary realisation of *Gaia*-CRF2 is the list of positions, as given in DR2, for a subset of 556 869 sources identified as quasi-stellar objects (QSOs), i.e. the optical emission from active galactic nuclei (AGNs) at cosmological distances. Their proper motions, also given in DR2, are usually insignificant and the reference frame was adjusted so that their global rotation (spin) is zero to within 0.02 mas yr^{-1}. 2820 of the QSOs were identified as the optical counterparts of ICRF sources in a prototype version of ICRF3 (Jacobs et al., 2018), and were used to align the positional system of *Gaia*-CRF2 with the ICRF to within about 0.02 mas at the epoch J2015.5.

An implicit assumption is that the positions and proper motions of all DR2 sources are on the same reference frame, providing a secondary, much denser realisation of *Gaia*-CRF2 for all magnitudes in the range $G \simeq 3$–21. However, the quality of the reference frame cannot easily be checked except for the QSOs, which are all fainter than $G \simeq 13$, and 99.9% fainter than $G = 16$ mag. The QSOs are, in every respect, observed and treated exactly as ordinary stars of similar magnitude and colour, and it is therefore reasonable to assume that the levels of non-rotation and alignment errors quoted above apply also to the stellar part of *Gaia*-CRF2 fainter than $G \simeq 16$. As shown below, they do not apply, though, to stars brighter than $G \simeq 13$.

An important question is then how *Gaia*-CRF2, and indeed all future versions of the *Gaia* CRF, can be validated for sources brighter than $G \simeq 16$. In this paper I argue that accurate VLBI astrometry of radio stars can be used for this purpose, but that a concerted and well-planned programme of such observations in the next 5–10 years is needed to match the expected improvements in future versions of the *Gaia* CRF.

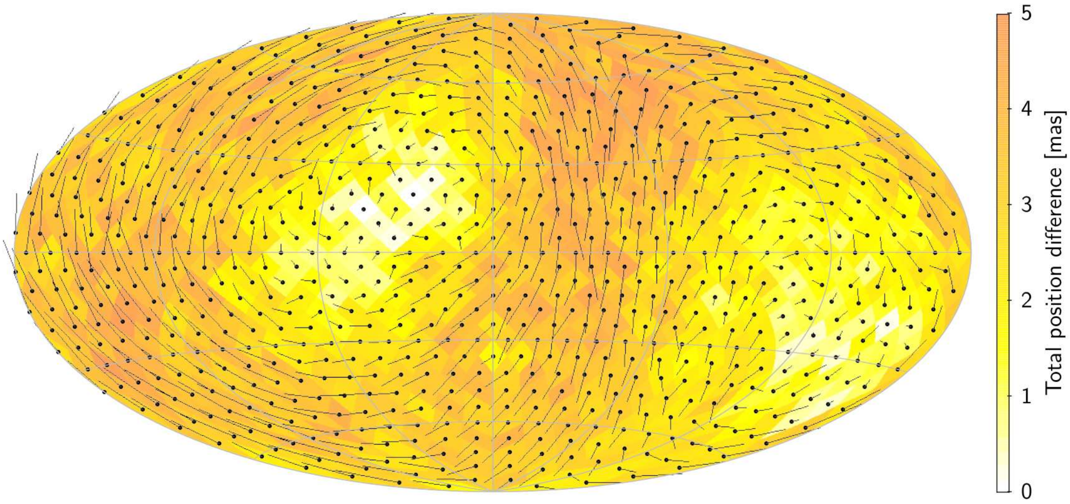

Figure 1: Position differences at epoch J1991.25 between *Gaia* DR2 and the Hipparcos Catalogue. The fans show the median displacements ($\alpha_{\rm DR2} - \alpha_{\rm Hip}, \delta_{\rm DR2} - \delta_{\rm Hip}$), magnified a factor 10^7, in cells of $\simeq 54\,\deg^2$ solid angle. The cells are coloured according to the total median displacement in the cell. The map uses the Hammer–Aitoff projection in equatorial (ICRS) coordinates with $\alpha = \delta = 0$ at the centre, north up, and α increasing from right to left.

2. THE BRIGHT REFERENCE FRAME OF GAIA DR2

Already at the time when *Gaia* DR2 was published, it was known that the reference frame for the bright sources ($G \lesssim 13$) has a significant ($\simeq 0.15$ mas yr^{-1}) spin relative to the quasars. This was seen from a comparison (Fig. 4 in Lindegren et al., 2018) with proper motions from the *Tycho–Gaia* Astrometric Solution (TGAS) of DR1. In TGAS the proper motions were obtained by incorporating positions from the Hipparcos and *Tycho*-2 catalogues in the solution, thus benefiting from the ∼24 yr epoch difference (Michalik et al., 2015).

The issue is illustrated in Fig. 1. This shows the systematic differences in the positions of Hipparcos stars between *Gaia* DR2 and the Hipparcos Catalogue (van Leeuwen, 2007). The position comparison is made at the reference epoch of the Hipparcos Catalogue, J1991.25, by propagating the *Gaia* DR2 positions back to this epoch, using the proper motions in DR2. The pattern shows a very clear signature of rotation, by about 3.6 mas around the direction $(\alpha, \delta) = (53^\circ, +15^\circ)$. There are three possible explanations for this global pattern: (i) a misalignment of the Hipparcos Catalogue at J1991.25 with respect to the ICRS by 3.6 mas; (ii) a similar but opposite misalignment of the *Gaia* DR2 positions at J2015.5; or (iii) a spin of the DR2 proper motions relative to ICRS by about (3.6 mas)/(24.25 yr) $\simeq 0.15$ mas yr^{-1}. From the way the Hipparcos Catalogue was aligned with ICRS (Kovalevsky et al., 1997), explanation (i) is very unlikely (formally, the probability is $< 10^{-6}$), and (ii) can be ruled out on similar grounds (cf. Sect. 3). Although a minor part of the effect could be explained by a combination of (i) and (ii), we must conclude that (iii) is the main cause, i.e. that the bright reference frame of DR2 rotates with respect to ICRS at a rate of about 0.15 mas yr^{-1}.

To further quantify this rotation, Fig. 2 shows the equatorial components of the global spin vector $[\omega_X, \omega_Y, \omega_Z]$ calculated in bins of the G magnitude. For $G \gtrsim 16$ the reference frame is non-rotating to < 0.02 mas yr^{-1}. Between $G = 14$ and 16 some deviation in ω_Y is indicated, although the number of QSOs is too small to allow a firm conclusion. For $G \lesssim 13$ the spin is very significant, and almost constant between $G = 7$ and 11. From $G = 11$ to 13 the data are too noisy to tell with certainty if there is a progressive transition to the faint reference frame. The combined

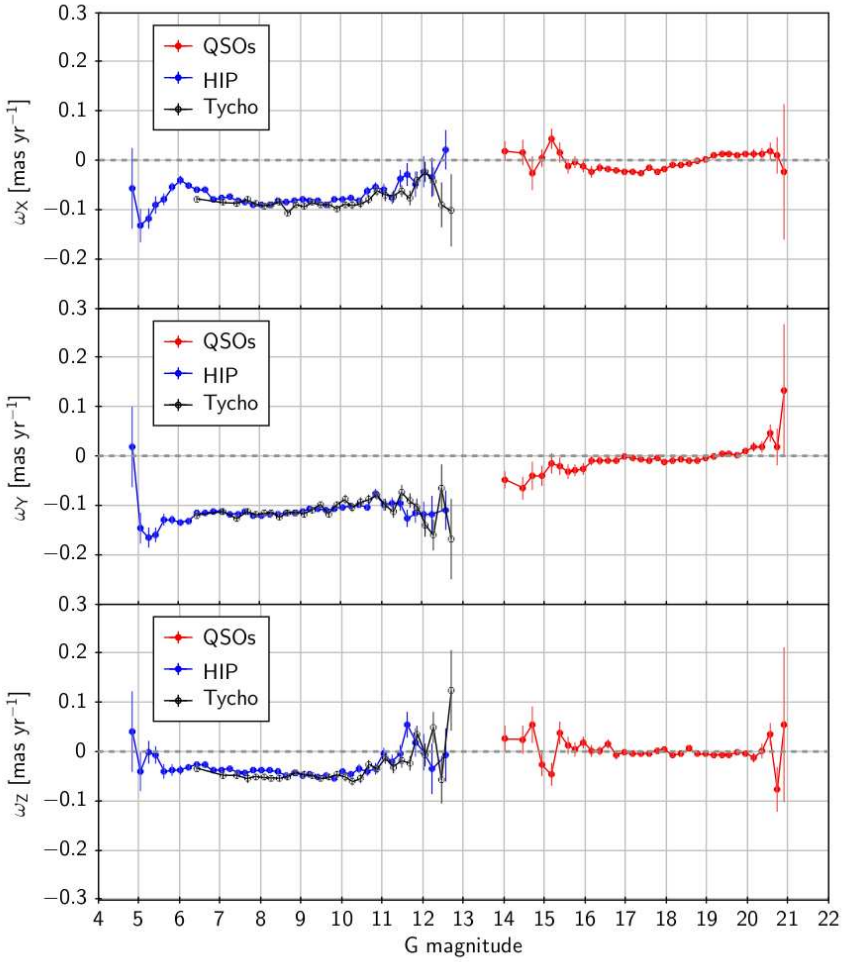

Figure 2: Estimates of the global spin of the *Gaia*-CRF2 as a function of G. For sources fainter than $G \simeq 14$ (in red), the spin is estimated from the proper motions of QSOs; for brighter sources it is computed from the differences between the *Gaia* DR2 proper motions of Hipparcos stars (blue) and *Tycho*-2 stars (black) and their proper motions derived from the position differences DR2 − Hip and DR2 − Tyc, divided by the epoch difference of 24.25 yr.

result, using the ~90 000 best-fitting Hipparcos stars, is:

$$\boldsymbol{\omega} \equiv \begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} = \begin{bmatrix} -0.085 \pm 0.025 \\ -0.113 \pm 0.025 \\ -0.039 \pm 0.025 \end{bmatrix} \text{ mas yr}^{-1}, \qquad (1)$$

where the uncertainties follow from the estimated RMS alignment error of the Hipparcos Catalogue at J1991.25 (0.6 mas per axis; Kovalevsky et al., 1997) divided by the epoch difference. The vector (1) is a correction to the DR2 proper motions in the following sense:

$$\left.\begin{aligned} \mu_{\alpha*}^{\text{ICRF}} &= \mu_{\alpha*}^{\text{DR2}} + \omega_X \cos\alpha \sin\delta + \omega_Y \sin\alpha \sin\delta - \omega_Z \cos\delta \\ \mu_{\delta}^{\text{ICRF}} &= \mu_{\delta}^{\text{DR2}} - \omega_X \sin\alpha + \omega_Y \cos\alpha \end{aligned}\right\} \qquad (2)$$

Note that this correction only applies to sources brighter than $G \simeq 13$.

3. USING VLBI ASTROMETRY OF RADIO STARS

The classical method to estimate the spin ($\boldsymbol{\omega}$) of a catalogue is to derive absolute proper motions for some objects, e.g. using VLBI, calculate the proper motion differences with respect to the catalogue, and finally use equations like (2) to solve the components ω_X, ω_Y, ω_Z by least squares (e.g. Bobylev, 2019). This method does not use any positional information contained in the VLBI data, except for the differential measurements from which proper motions are derived.

But even without any associated proper motions, positional VLBI observations can contribute to the determination of $\boldsymbol{\omega}$, just like the Hipparcos positions did for (1), provided that they are made at an epoch sufficiently different from the *Gaia* epoch. The greater the epoch difference, the more weight is contributed by the VLBI positions to the determination of $\boldsymbol{\omega}$. The early phase-referencing VLBI observations by Lestrade et al. (1999) are thus particularly valuable, as their mean epochs in the early 1990s provide a time baseline of more than two decades to the *Gaia* observations. Future VLBI observations, even many years after the *Gaia* mission has ended, will for the same reason be extremely valuable for the determination of the spin. Note that the VLBI positions at various epochs need not refer to the same sources, since the information on $\boldsymbol{\omega}$ comes from their positional differences with respect to *Gaia*.

Lindegren (2020) describes a general algorithm to estimate the spin ($\boldsymbol{\omega}$) and orientation error ($\boldsymbol{\varepsilon}$) of a stellar catalogue by means of VLBI observations. It determines by least squares the six constants in the linear expression

$$\boldsymbol{\varepsilon}(t) = \boldsymbol{\varepsilon}(T) + (t - T)\boldsymbol{\omega} \tag{3}$$

for the orientation error relative to the ICRS as a function of time, where T is the reference epoch of the *Gaia* data. Applied to *Gaia* DR2 ($T = 2015.5$), using VLBI data for 41 radio stars collected from the literature, the result is

$$\boldsymbol{\varepsilon}(2015.5) = \begin{bmatrix} -0.35 \pm 0.14 \\ +0.36 \pm 0.25 \\ +0.05 \pm 0.05 \end{bmatrix} \text{mas}\,, \qquad \boldsymbol{\omega} = \begin{bmatrix} -0.077 \pm 0.051 \\ -0.096 \pm 0.042 \\ -0.002 \pm 0.036 \end{bmatrix} \text{mas yr}^{-1}\,. \tag{4}$$

In this solution only 26 of the 41 radio stars were retained; 15 were iteratively rejected based on a goodness-of-fit criterion. Most of the rejected sources are known to have significantly non-uniform motions due to perturbing companions.

Within its uncertainty, the result for $\boldsymbol{\omega}$ in Eq. (4) agrees with the spin (1) obtained from the Hipparcos positions. It therefore supports the conclusion in Sect. 2 concerning the rotation of the bright reference frame of *Gaia* DR2. The two determinations of $\boldsymbol{\omega}$ are in fact not entirely independent: the alignment of the Hipparcos Catalogue at J1991.25 to the ICRS mainly relied on the VLBI observations of 12 radio stars made by Lestrade et al. between 1984 and 1994 (Kovalevsky et al., 1997), and several of them also contribute heavily to (4), as discussed below.

4. THE VALUE OF OLD (AND FUTURE) VLBI OBSERVATIONS

The algorithm described in Lindegren (2020) also computes quantities E_i and Ω_i representing the statistical weights contributed by the VLBI data on each radio star (i) to the determination of $\boldsymbol{\varepsilon}(2015.5)$ and $\boldsymbol{\omega}$, respectively (or, in the case of a rejected object, the potentially contributed weight). Figure 3 shows these quantities plotted against the mean epoch of the VLBI observations. From Fig. 3a it is evident that the orientation at epoch J2015.5 is almost entirely determined by VLBI observations made close to this epoch. This is expected, since the older VLBI data only contribute to $\boldsymbol{\varepsilon}(2015.5)$ if their proper motions are good enough to provide positions at J2015.5 of competitive precision, which is usually not the case.

By contrast, in Fig. 3b more than half of the total weight contributed towards the determination of $\boldsymbol{\omega}$ comes from the six accepted objects with pre-1995 VLBI data, thanks to their large epoch

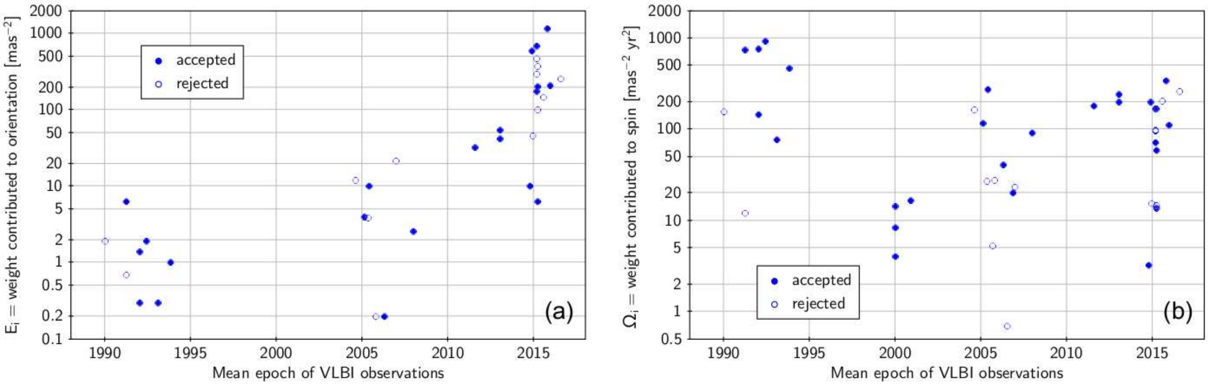

Figure 3: Weights contributed by the VLBI data for the 41 radio stars considered by Lindegren (2020) to the estimation of **(a)** the orientation at J2015.5, and **(b)** the spin of the bright reference frame of *Gaia* DR2. Filled and open circles denote sources accepted and rejected in the solution.

differences with respect to the *Gaia* data. In order of decreasing Ω_i, these objects are: AR Lac, LS I +61 303, Cyg X-1, HD 199178, HD 22468, and BH CVn (HR 5110). All of them were observed by Lestrade et al. (1999) with typical positional uncertainties of 0.3–0.5 mas at their respective mean epoch. Recent programmes such as the GOBELINS survey (e.g. Kounkel et al., 2017) often reach positional uncertainties that are ten times smaller, but because their mean epochs are close to the *Gaia* DR2 epoch they mainly contribute (in this analysis) to the determination of $\boldsymbol{\varepsilon}(2015.5)$, as shown in Fig. 3a. However, as more observations of a similar accuracy will surely be added to the analysis in coming years, the determination of $\boldsymbol{\omega}$ will increasingly rely on the recent data.

Nevertheless, in spite of expected improvements in future VLBI data, the old observations will not become obsolete. Most of the radio stars are close binaries (e.g. of RS CVn type), and many have a third component in a long-period orbit causing a significant acceleration in the motion of the close pair. This is the case e.g. for σ^2 CrB and UX Ari, two well-observed objects in the Lestrade et al. programme that were rejected in the present analysis due to their bad goodness-of-fit statistics. With a more sophisticated modelling of their motions, these objects could well be included in future analyses, in which case the early data will be extremely valuable.

For the present analysis it was sometimes possible to increase, by a large factor, the weight of an early VLBI position simply by recalculating it, using the most recent (ICRF3) position for the calibrator source (the quasar used for the phase referencing). One example is Cyg X-1, where the positional uncertainty at 1991.25 was reduced from ≃1.5 mas, as given in Lestrade et al. (1999), to the ≃0.35 mas used in this analysis. This is of course only possible when the identity and position of the calibrator, as used in the original VLBI reduction, have been documented.

5. CONCLUSION

Based on a comparison with accurate VLBI astrometry of radio stars, it is concluded that the bright ($G \lesssim 13$ mag) reference frame of *Gaia* DR2 is rotating with respect to quasars at a rate of about 0.15 mas yr^{-1}. This supports a similar conclusion based on a comparison with Hipparcos positions at the epoch J1991.25. On the other hand, QSO data show that the faint ($G \gtrsim 16$) reference frame of *Gaia* DR2 is non-rotating at <0.02 mas yr^{-1}. The difference between the bright and faint reference frames is related to the different modes of observation (CCD sampling) in *Gaia*, and associated calibration issues that will only be resolved in future releases (see Appendix B in Lindegren, 2020, for details).

The comparison of *Gaia* DR2 data with VLBI astrometry uses a new algorithm that incorporates in an optimal way both positional information and proper motions in a single solution of the orientation ($\boldsymbol{\varepsilon}$) and spin ($\boldsymbol{\omega}$) of the *Gaia* reference frame with respect to the ICRS.

It is expected that the the celestial reference frame will be an order of magnitude more precise in the final release of *Gaia* data than it is in DR2. To validate the bright reference frame of future releases to a matching accuracy will be challenging. Clearly it will not be enough to compare with the Hipparcos reference frame, which will not improve with time. Instead, the validation must rely mainly on existing and future VLBI astrometry of radio stars. This will require many more positional measurements to be obtained in the next 5–10 years, on an absolute accuracy level of $\simeq$0.1 mas or better, with direct links to the ICRF frame. To minimise the impact of multiplicity, it will be prudent to use as many different sources as possible. While most of the new positional VLBI data could materialise as a by-product of various astrophysical programmes, it may be necessary to complement them with dedicated observations targeting specific objects, such as astrometrically "clean" radio stars (ideally single main-sequence stars), objects with a long history of accurate VLBI observations, and radio stars with optical magnitudes in the range 13 to 16, which are rare in current programmes.

Irrespective of their original scientific motivation, it is important that astrometric VLBI observations are published in sufficient detail, and with adequate meta-information, so that they can be used in the future to address other scientific questions, including those related to the radio-optical reference frame. As a minimum, the positions derived from the individual observing sessions should be given, with their mean epochs of observation, as well as the assumed positions of the calibrators. Most, but not all recent publications already provide this information.

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