The bright reference frame of Gaia and VLBI observations of radio stars

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The reference frame of *Gaia* DR2: *Gaia*-CRF2

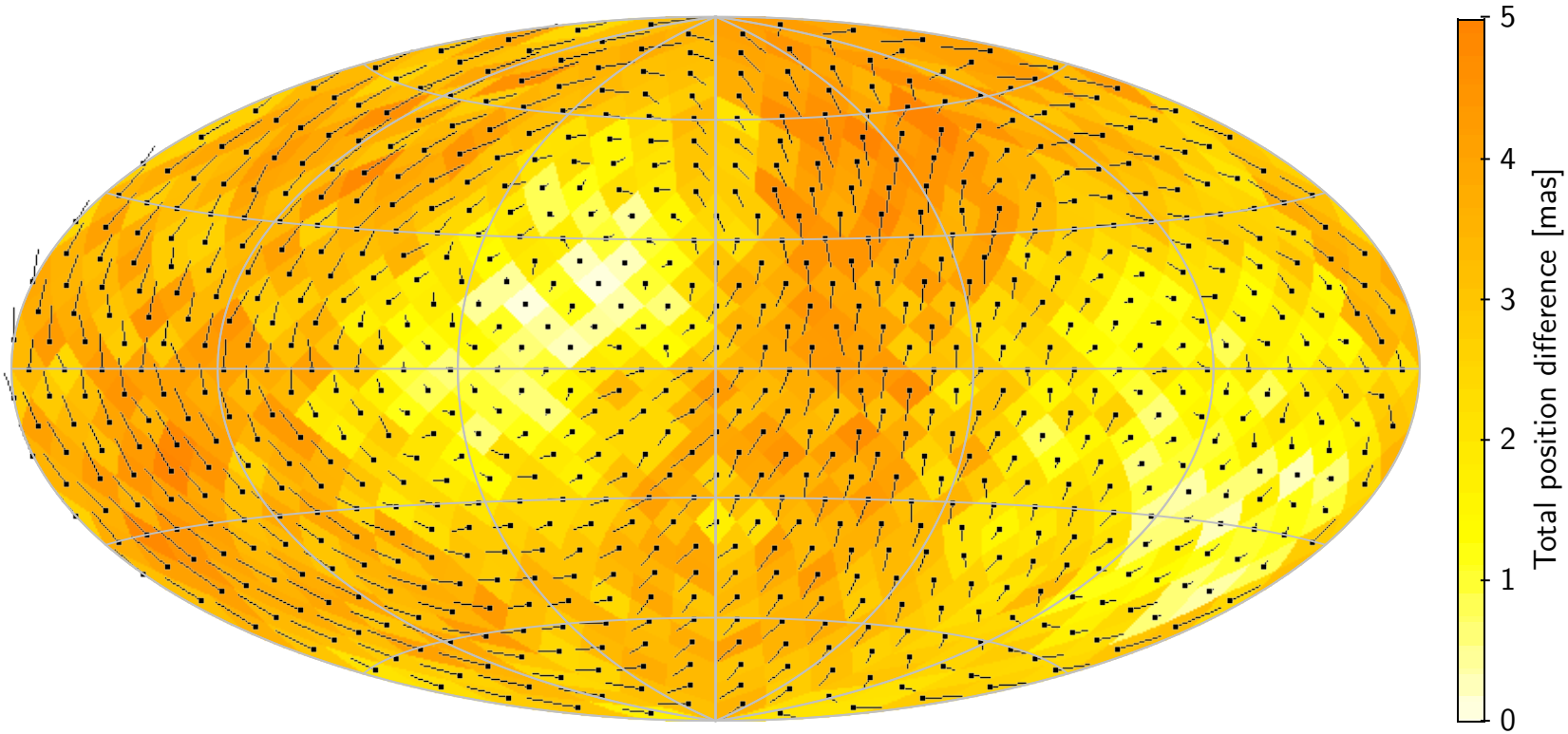
- The primary realisation of *Gaia*-CRF2 is a list of the positions for 556 869 quasars at epoch J2015.5
  (Gaia Collaboration et al. 2018, A&A 616, A14)
- The implicit assumption is that the positions and proper motions of *all* DR2 sources are on the same reference frame, providing a secondary, much denser realisation of *Gaia*-CRF2 for all magnitudes
- The quality of *Gaia*-CRF cannot easily be checked except for the quasars – and 99.90% of them are fainter than 16th mag ($G > 16$)

How can the *Gaia*-CRF be validated
for sources brighter than 16th magnitude?

Comparing stellar positions in *Gaia*-DR2 and HIP

Position differences *Gaia*-DR2 − HIP at J1991.25

Vectors $= (\overline{\Delta\alpha}, \overline{\Delta\delta})$, colour scale $= \left(\overline{\Delta\alpha}^2 + \overline{\Delta\delta}^2\right)^{1/2}$



$\Rightarrow$ rotation by $\sim$3.6 mas around $(\alpha, \delta) = (53^\circ, +15^\circ)$

Inferred spin of the bright ($G < 13$) *Gaia*-CRF2

The mean spin inferred from the comparison with Hipparcos is

$$\boldsymbol{\omega} \equiv \begin{bmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{bmatrix} = \begin{bmatrix} -0.086 \pm 0.025 \\ -0.114 \pm 0.025 \\ -0.037 \pm 0.025 \end{bmatrix} \text{ mas yr}^{-1}$$

$\boldsymbol{\omega}$ is a correction in the sense

$$\left.\begin{aligned} \mu_{\alpha*}^{\text{ICRF}} - \mu_{\alpha*}^{\text{DR2}} &= +\omega_X \cos\alpha \sin\delta + \omega_Y \sin\alpha \sin\delta - \omega_Z \cos\delta \\ \mu_{\delta}^{\text{ICRF}} - \mu_{\delta}^{\text{DR2}} &= -\omega_X \sin\alpha \qquad\quad + \omega_Y \cos\alpha \end{aligned}\right\} \quad (1)$$

Note:
This correction applies only to bright sources ($G < 13$ mag) in *Gaia*-DR2.

Brandt (ApJS, 239, 31, 2018) derived a very similar correction from HIP

Estimating the spin using VLBI of radio stars

Classical method to estimate the spin ($\boldsymbol{\omega}$) of a catalogue:

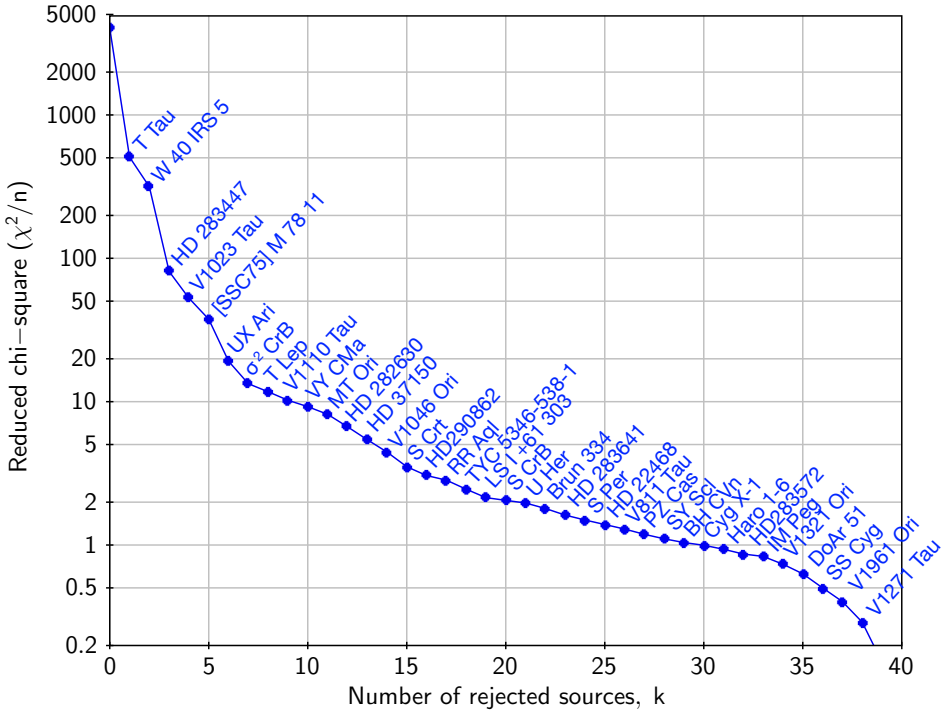
- derive "absolute" proper motions for some objects (e.g. using VLBI)
- calculate proper motion differences with respect to the catalogue
- solve $(\omega_X, \omega_Y, \omega_Z)$ by least-squares from equations like (1)

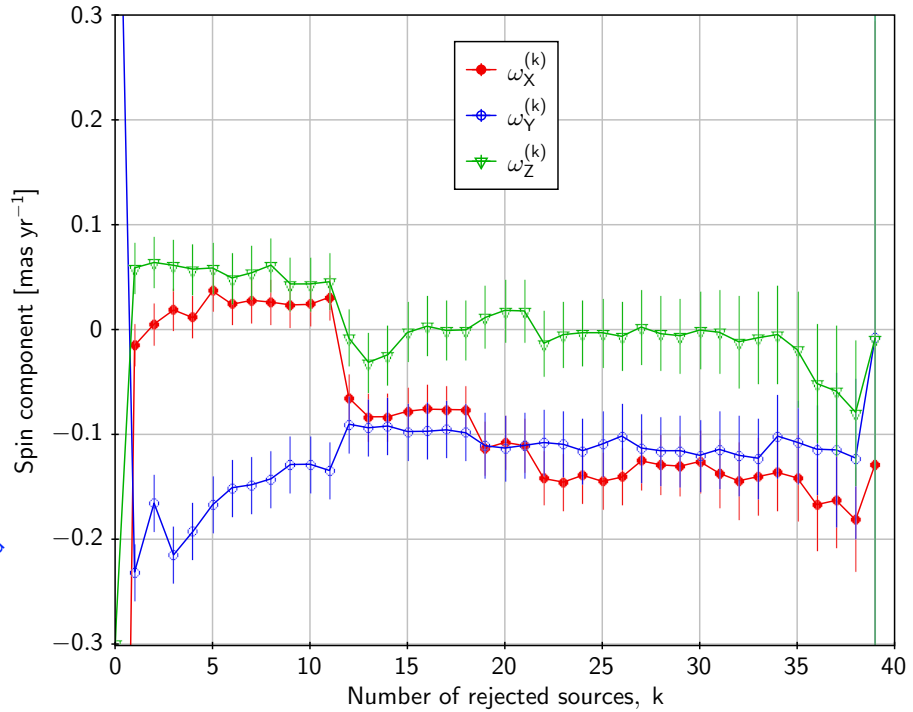
Important insights:

- it is not necessary to derive (absolute) proper motions by VLBI
- (barycentric) VLBI positions at earlier epochs can be used exactly as the Hipparcos positions
- even topocentric positions from individual VLBI sessions can be used (with *Gaia* parallaxes for the correction to the barycentre)
- orientation ($\boldsymbol{\varepsilon}$) and spin ($\boldsymbol{\omega}$) must be solved simultaneously

See Lindegren (arXiv:1906.09827) for details

Estimating the spin using VLBI of radio stars



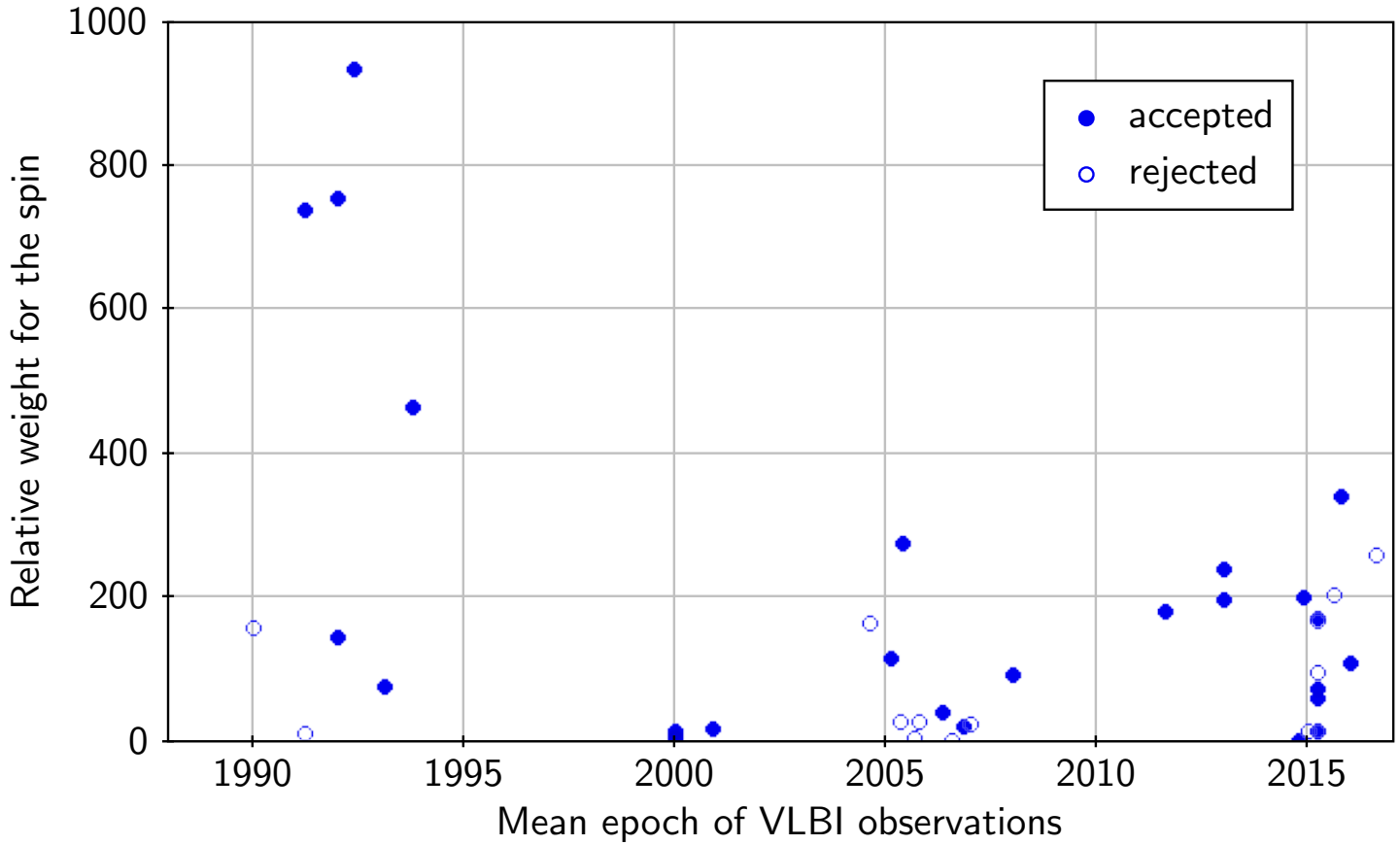


VLBI astrometry for 41 radio stars ($G < 13$) from the literature gives

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

(rejecting 15 stars); cf. $\boldsymbol{\omega} = (-0.086, -0.114, -0.037)$ from Hipparcos

The value of old (and future) VLBI observations



The early observations contribute much weight to the determination of ω, even though more recent observations are often more accurate

An old position observation can never be repeated!

Improving old VLBI data: Example Cyg X-1

Lestrade et al. (A&A, 344, 1014, 1999):
High-precision VLBI astrometry of radio-emitting stars

From their results table:

Star (Reference)	Epoch	$\Delta\alpha$(J2000) (h m s) α(J2000) (h m s)	$\Delta\delta$(J2000) (° ′ ″) δ(J2000) (° ′ ″)
$\Delta-$Cyg X1	910402	00 00 41.128564 ±0.000022	01 33 37.89682 ±0.00032
Cyg X1 (1955+335)	910402	19 58 21.678600 ±0.000101	35 12 05.84237 ±0.00175

From their table of extragalactic reference source positions:

Extragalactic source	α(J2000) (h m s)	δ(J2000) (° ′ ″)
1955+335	19 57 40.550036 ±0.000099	+33 38 27.94555 ±0.00148

Using modern (ICRF3) data for the position of 1955+335 improves the position uncertainty of Cyg X-1 @1991.25 from ∼1.5 mas to ∼0.4 mas

Why is the bright *Gaia*-CRF2 rotating?

- *Gaia* has several different modes of observation, depending (mainly) on the magnitude of the source: different CCD sampling schemes; use of blocking gates to reduce integration time
- In principle each mode corresponds to a different instrument, and a different calibration
- Mode overlap should ensure RF consistency across mode boundaries
- The model for $G < 13$ is much more complicated (2D, gates, pixel saturation, ...) and as yet far from satisfactory

The end result is a break in the RF at $G \simeq 13$.

Cure: improve the calibration model for bright sources!

Summary

- The faint ($G > 16$) part of *Gaia*-CRF2 is good to ± 0.02 mas yr^{-1}
- The bright ($G < 13$) part has a systematic spin of ~ 0.15 mas yr^{-1}
- Intermediate magnitudes ($13 < G < 16$) may be OK
- Current calibration for bright sources not good enough $\Rightarrow$ rotation
- Major improvements expected in future *Gaia* data releases
- Important to validate future *Gaia*-CRF across all magnitudes
- VLBI observations of radio sources is probably the only way
- Re-observation of current list in coming 5–10 years
- More radio stars desirable for better robustness, sky and G coverage
- Unique value of past positional observations (preserve, re-calibrate)

Further details in Lindegren (arXiv:1906.09827, submitted to A&A)