The impact of new models of stellar motion from VLBI on the alignment of the optically bright Gaia frame to ICRF3

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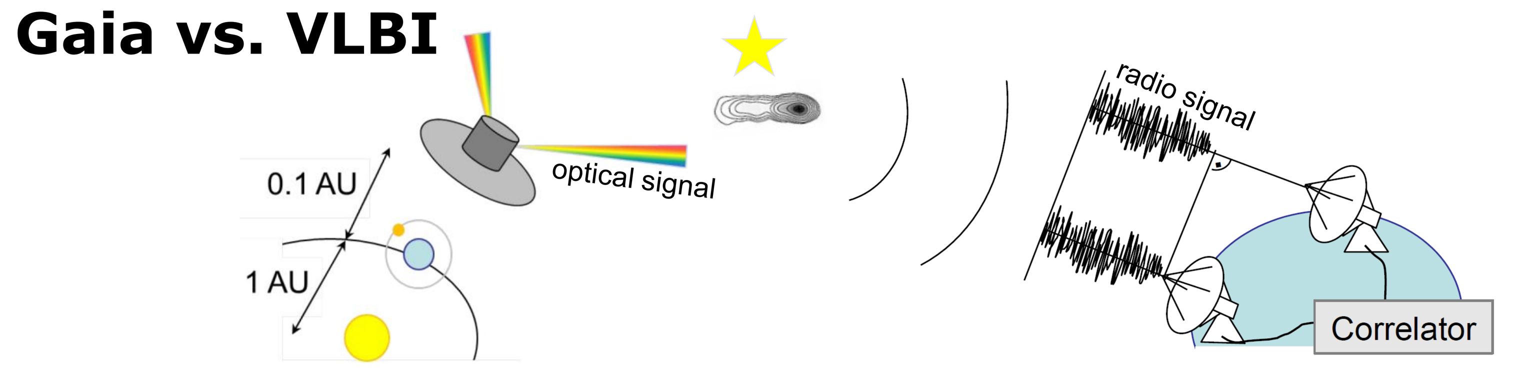
Abstract

The reference frame determined by Gaia EDR3 is aligned to the International Celestial Reference System by referring to counterparts in its latest realization, the third International Celestial Reference Frame (ICRF3), which is calculated from long baseline interferometry (VLBI) observations of extragalactic objects at radio frequencies. The objects in ICRF3, although bright at radio frequencies, are mostly faint at optical frequencies. The non-rotation of the optically bright Gaia frame to ICRF3 has to be tested by identifying additional counterparts besides objects in ICRF3 because the Gaia dataset is known to be magnitude-dependent in terms of astrometric calibration. Such counterparts are radio stars observed by VLBI relative to extragalactic objects in ICRF3 using phase-referencing. We discuss the rotational differences, i.e., orientation and spin, between the optically bright Gaia EDR3 and models of stellar motion from VLBI. In particular, we show the effects of improved models of stellar motion, for which we added new VLBI positions to time series from the literature and archives.

Gaia vs. VLBI



- Spacecraft	- Earthbound antennas
- Optical frequencies	- Multiple radio frequencies
- Operating since 2014	- Operation at S/X bands since 1979
- 5 parameters (position, proper motion, parallax)	- 2 parameters for reference frame (position), 5+ parameters possible

Magnitude dependence of the alignment

- Gaia has optical magnitude limits of about 3 mag < G < 21 mag
- The Gaia internal calibration of the bright sources (G < 13 mag) is independent from the calibration of the faint sources

→ **No matched ICRF3 source** is brighter G < 13 mag

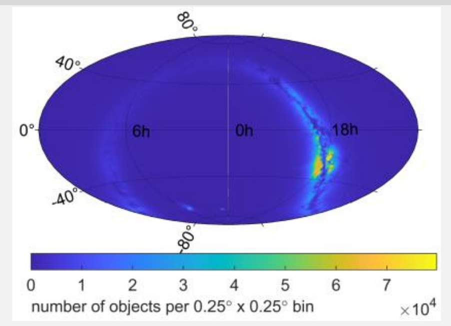
→ Rotation of the optically bright sources cannot be verified by ICRF3 **directly**

→ In Gaia EDR3 the spin of the bright frame was corrected to be zero with respect to the Hipparcos frame, with uncertainties of 600 µas (orientation) and 25 µas yr $^{-1}$ (spin) per axis

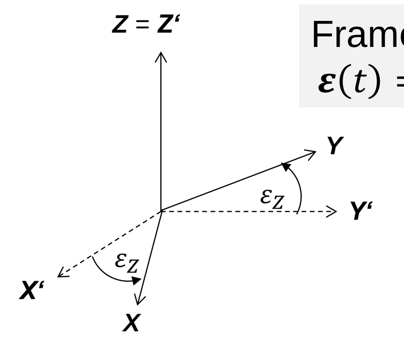
→ test if VLBI to optically bright radio stars will be more accurate

Alignment between ICRF and Gaia

Gaia EDR3 [*X' Y' Z'*]



Input: α(T), δ(T), μ_α(T), μ_δ(T), π(T) propagated to VLBI epoch t; v_r from SIMBAD

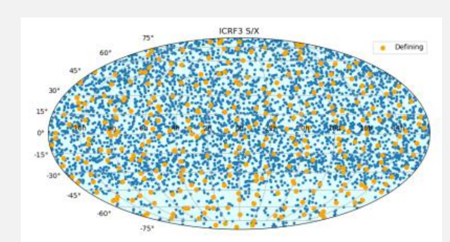


Frame rotation:
$\boldsymbol{\varepsilon}(t) = \boldsymbol{\varepsilon}(T) + (t - T) \cdot \boldsymbol{\omega}$

Output:

- instantaneous configuration (orientation) $\boldsymbol{\varepsilon}(T)$ and angular velocity (spin) $\boldsymbol{\omega}$
- adjusted parameters for VLBI

VLBI ICRF3 (S/X) [*X Y Z*]



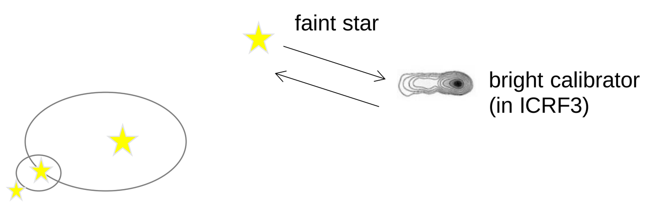
credit: hpiers.obspm.fr

Input: absolute position α(t), δ(t) **and/or** μ_α, μ_δ, π
→ important: α(t), δ(t) are used for the adjustment of orientation **and** spin

Available VLBI data

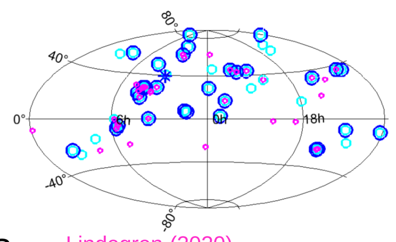
→ **Stars are optically bright but very faint at continuum radio frequencies**
→ Only very few are detectable by absolute geodetic VLBI
→ Relative measurement method of **phase-referencing VLBI** has to be employed

- Suitable VLBI continuum astrometric observations of stars are **sparse in spatio-temporal distribution**
- **Physical nature of stars** produces complications: radio-optical offsets, high variability, multiple star systems (orbital motion, acceleration terms)



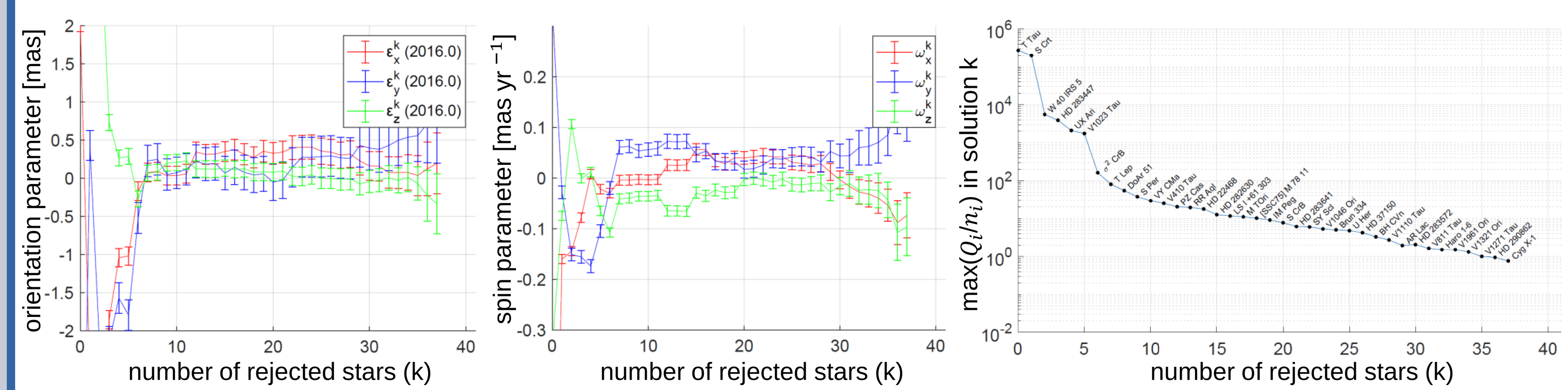
1) Collection of VLBI data for **41 stars** from Lindegren (2020)
2) Additional position in January 2020 for **32 detected** stars with the VLBA (US Naval Observatory's time allocation) at X- or C-band

- **Homogeniously** referenced to ICRF3 → absolute positions of stars in ICRF3
- Galactocentric acceleration effect handled in star positions and proper motions
- **Consistent realistic error budget** applied to absolute positions



Lindegren (2020)
Observed January 2020
Detected January 2020

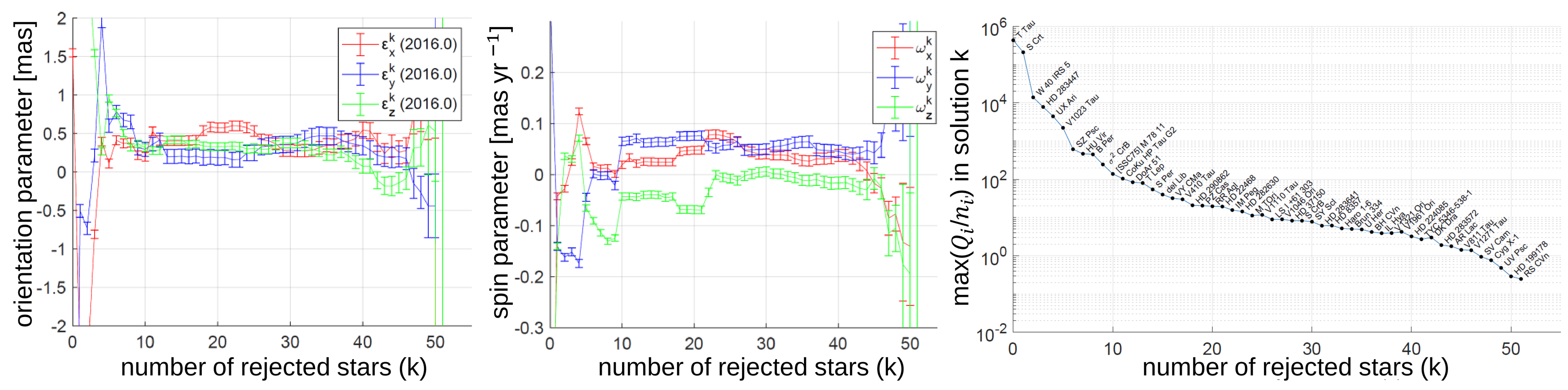
1) Alignment using 41 stars from Lindegren (2020)



Iterative solutions for the orientation and spin parameters, where in each iteration the most deviating star k with max(Q_i/n_i) gets rejected from the sample. After iteration k=7 the most obvious outlier stars are excluded. Still, jumps larger than the formal errors are present (k=12).

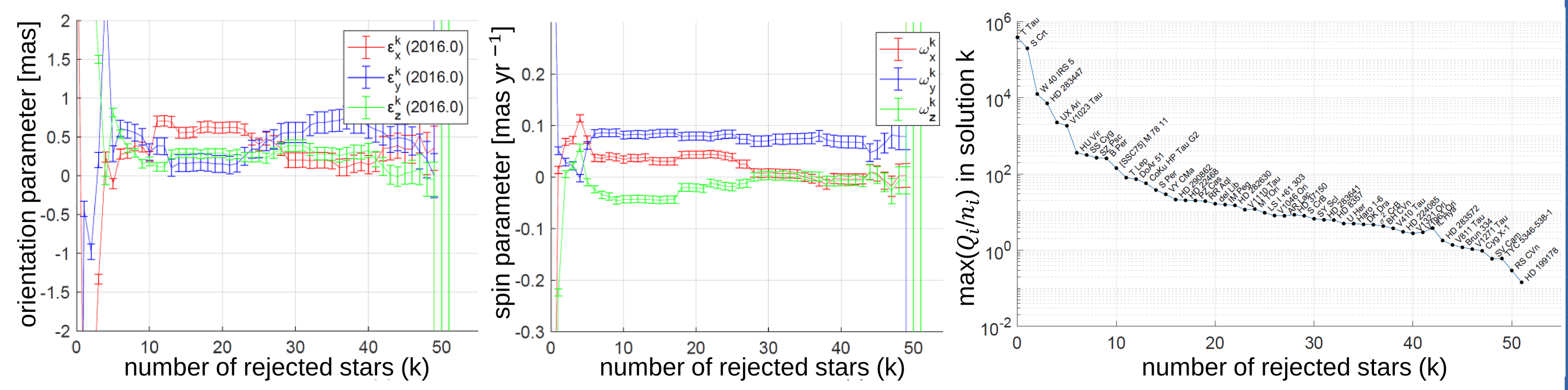
- In each of the solutions 1), 2a), and 2b), a different order of rejected stars is possible!

2a) Alignment using 1) + one-epoch absolute positions for 32 stars



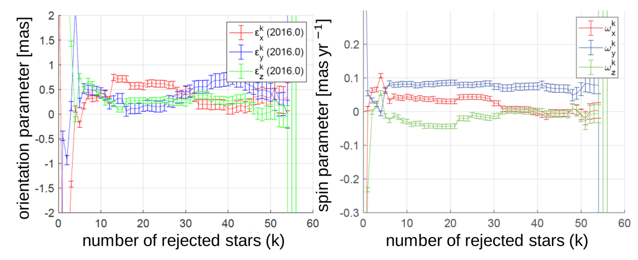
- Point-shape calibrator model applied (like for ICRF3)
- Formal uncertainties of rotation parameters decrease
- Significant correlations decrease (ε_X & ε_Y, ε_Y & ε_Z, ε_X & ω_X, ε_Y & ω_Y, ε_Z & ω_Z)

2b) Alignment using 1) + one-epoch absolute positions for 32 stars + improved models of stellar motion for 13 stars



- Replaced proper motion and parallax data by new models (a) – (m)
- Replaced positions by positions from a)
- Now zero correlation between $\boldsymbol{\varepsilon}$ & $\boldsymbol{\omega}$
- Spin more stably determined

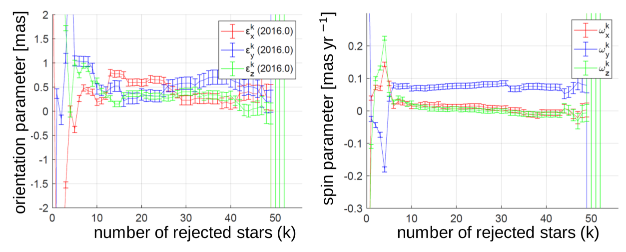
3) Including additional stars to 2b)



- From LBA and other VLBI networks

• del Lib: full model (o), HD 142184: μ_α, μ_δ, π from (n), HD 167971: 2 positions, V479 Sct, EI Eri: 1 position, YY Men: 1 position, 1 position from **absolute geodetic VLBI**

4) Excluding 4 stars which cause jumps

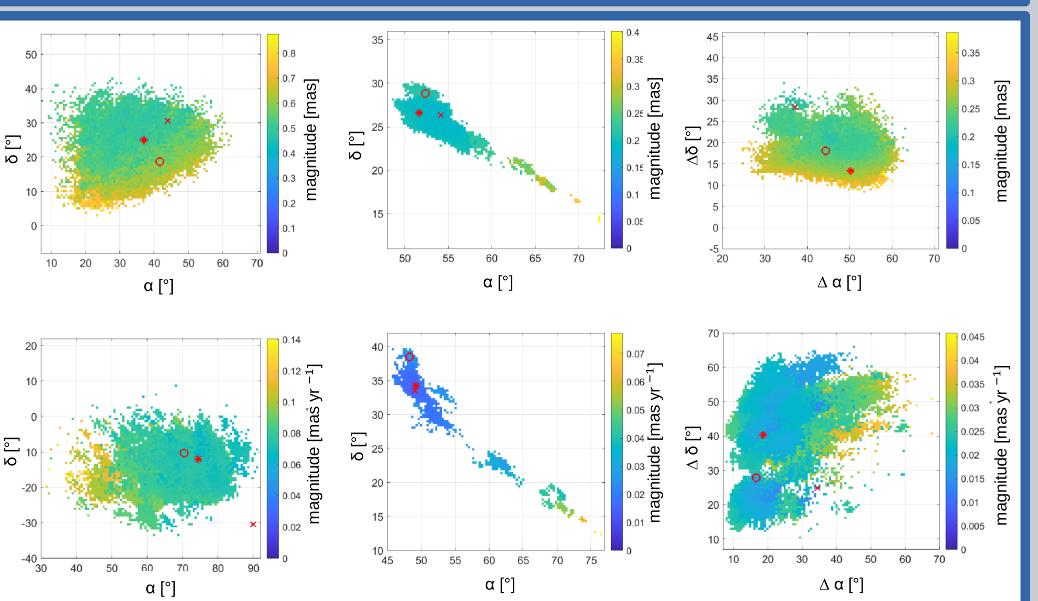


- HD 22468, IM Peg, AR Lac, LSI +61 303 excluded

→ **stable estimates of significant residual spin between ICRF3 & Gaia EDR3 of $\omega_Y \approx +0.074 \pm 0.008$ mas yr $^{-1}$**

Evaluation of the results

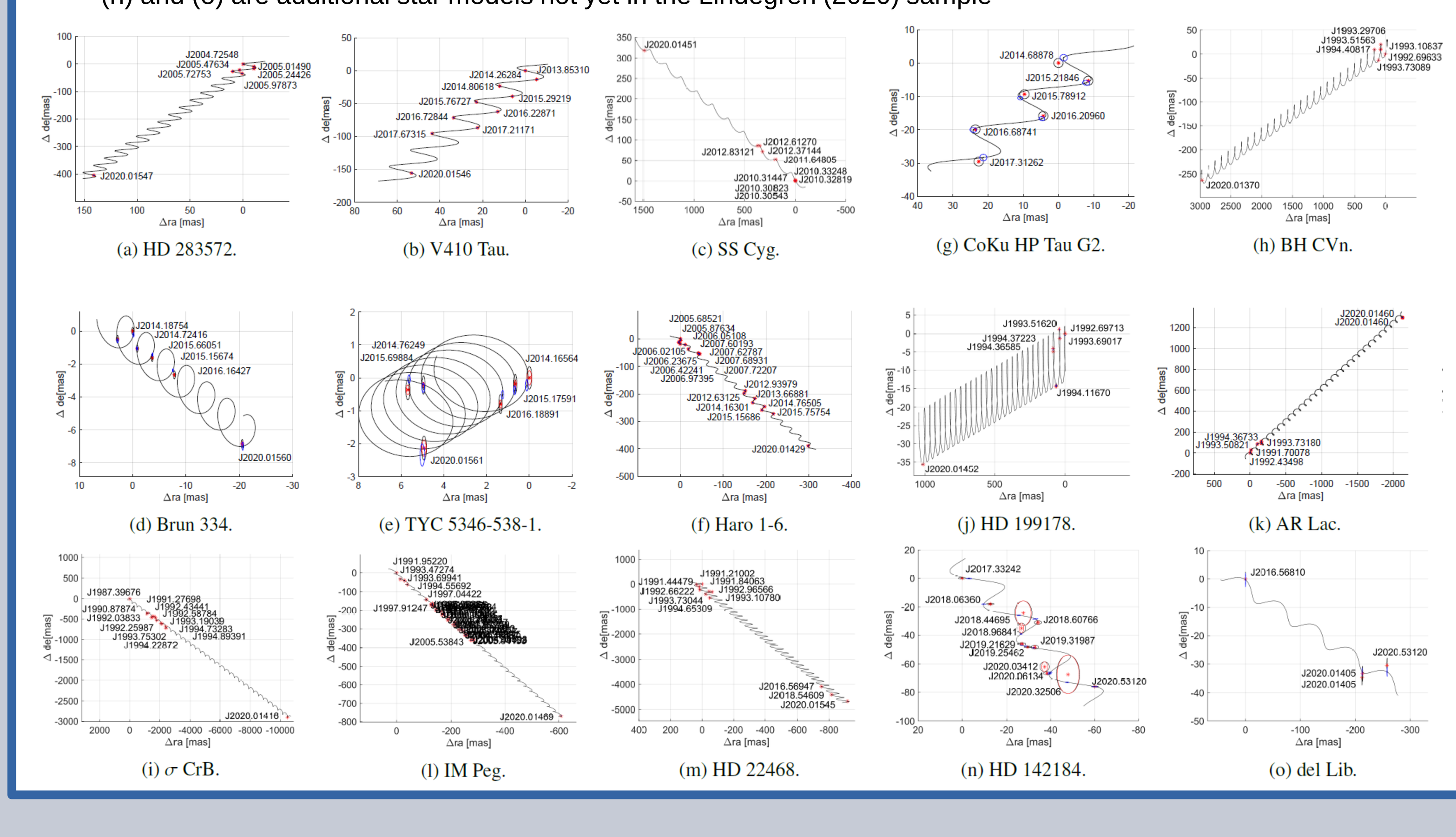
- Using only stars from iterations 11 onwards from scenario 3) and excluding 4 additional stars from the beginning → 211877 scenarios
- Calculated weighted mean (WM), mean formal error (ME), and weighted root mean square of estimates around the WM (WRMS) for each scenario. The last 10 iterations were neglected each
- Plots show these metrics for the orientation and spin vectors for all scenarios
- The red crosses label the respective minimum magnitude; The red circles label results of 4); The red stars label the scenario with minimum sum of all Q/n of its iterations
- ~ 0.5 ± 0.2 mas for orientation and ~ 0.07 ± 0.01 mas yr $^{-1}$ for spin
- WRMS ~ 0.2 mas for orientation and ~ 0.01 mas yr $^{-1}$ for spin



WM ME WRMS around WM

New models of stellar motion

- Combination of archived and new relative positions
- Structure-corrected calibrator models applied
- The observed positions are marked with a red star and their uncertainties by the black ellipse. The adjusted positions are labeled by a black dot and their uncertainties by a blue ellipse. The model is indicated by a black line.
- (n) and (o) are additional star models not yet in the Lindegren (2020) sample



(a) HD 283572. (b) V410 Tau. (c) SS Cyg. (g) CoKu HP Tau G2. (h) BH CVn.
(d) Brun 334. (e) TYC 5346-538-1. (f) Haro 1-6. (j) HD 199178. (k) AR Lac.
(i) σ CrB. (l) IM Peg. (m) HD 22468. (n) HD 142184. (o) del Lib.

Conclusions and outlook

- VLBI provides more than twice as accurate spin parameters than method applied during Gaia EDR3 processing
- Difference Gaia bright frame to ICRF3 is ~ 0.5 ± 0.2 mas for orientation and ~ 0.07 ± 0.01 mas yr $^{-1}$ for spin
- Proper motions, based on the far more accurate VLBI relative positions, contribute more to the spin determination than single-epoch positions with large absolute position uncertainties.
- Positions of more stars are needed in order to better determine orientation ε_X and ε_Y
- More accurate and precise VLBI data are needed in order to better identify outlier counterparts and to improve the reliability of the results

References and Acknowledgements

Lindegren (2020), A&A 633, A1

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