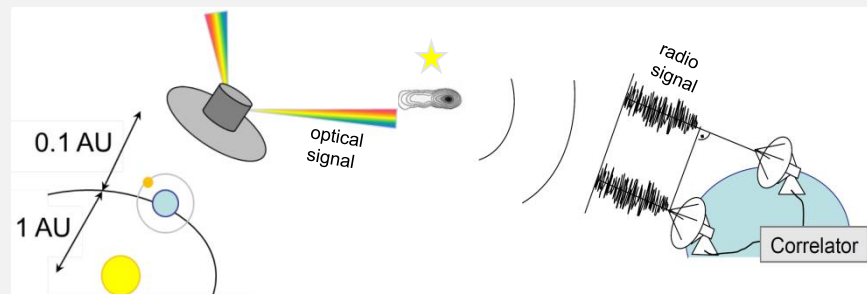


Linking the optically bright Gaia frame to the third International Celestial Reference Frame

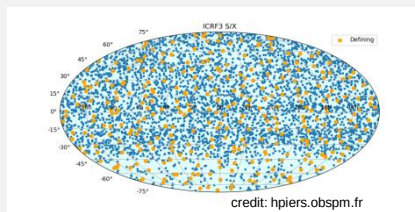
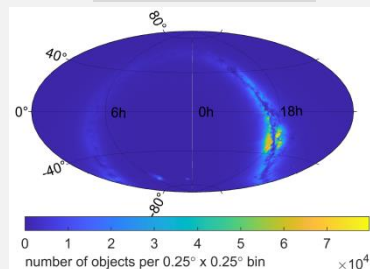
[Susanne Lunz](#)¹, James Anderson^{2,1}, Ming H. Xu^{3,4,2}, Robert Heinkelmann¹, Oleg Titov⁵, Megan Johnson⁶, and Harald Schuh^{2,1}

This presentation is interactive!



Gaia satellite

VLBI



Gaia catalog is aligned to ICRF3

Problem:

- Gaia catalog alignment is magnitude dependent
 - ICRF3 covers only optically faint objects
- How good is the alignment of the optically bright Gaia catalog to ICRF3?

Solution:

- Orientation and spin between the two catalogs by use of relative VLBI observations of optically bright radio stars towards a calibrator in ICRF3

Topics covered:

- Optically bright radio-optical counterparts
- Homogenization of existing suitable VLBI data
- Realistic error budget
- New dedicated VLBI observations (relative astrometry, not classical geodetic absolute VLBI)
- Impact of Galactic aberration
- Consequences for the user

Linking the optically bright Gaia frame to the third International Celestial Reference Frame

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⁵ Geoscience Australia, PO Box 378, Canberra 2601, Australia

⁶ United States Naval Observatory (USNO), 3450 Massachusetts Ave NW, Washington, DC 20392, USA

`susanne.lunz@gfz-potsdam.de`

General Assembly of the European Geosciences Union 2021

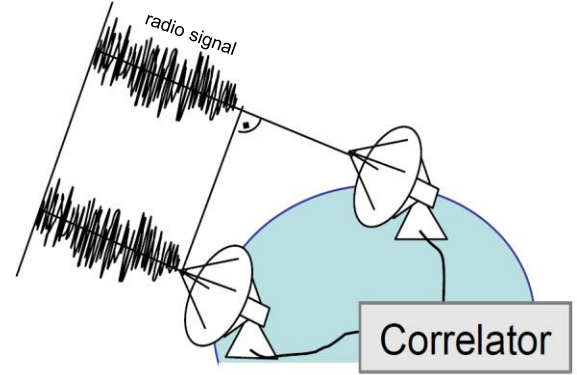
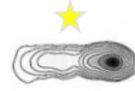
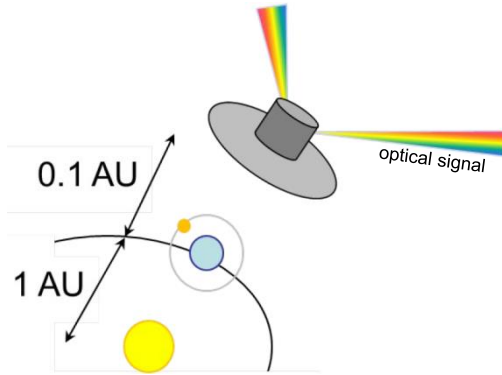
Session G6.1, EGU21-8604

Abstract

The new data release of the Gaia satellite operated by the European Space Agency recently published its 3rd data release (Early Data Release 3, EDR3, Gaia Collaboration (2020)). The dataset contains astrometric data of about 1.8 billion objects detected at optical frequencies, and therefore it is the largest catalog of astrometric information to date. The reference frame defined by Gaia EDR3 is aligned to the International Celestial Reference System (ICRS) by referring to counterparts in its realization, the third International Celestial Reference Frame (ICRF3, Charlot et al. (2020)), which is calculated from very long baseline interferometry (VLBI) observations of extragalactic objects at radio frequencies.

The Gaia dataset is known to be magnitude-dependent in terms of astrometric calibration. As the objects in ICRF3, although bright at radio frequencies, are mostly faint at optical frequencies, the optically bright Gaia frame has to be linked to ICRF3 by additional counterparts besides objects in ICRF3. The non-rotation of the optically bright Gaia frame is especially important as optically bright objects can, besides astrophysical studies, be used for navigation in space, where other geodetic systems like global navigation satellite systems are out of reach. Suitable additional counterparts are radio stars which are observed by VLBI relative to extragalactic objects in ICRF3. We discuss the orientation and spin differences between the optically bright Gaia EDR3 and VLBI data of radio stars and their impact on the Gaia data usage.

Gaia vs. VLBI



- Satellite in space

- Optical frequencies

- Operating since 2014

- 5 parameters (position, proper motion, parallax)

- Earthbound antennas

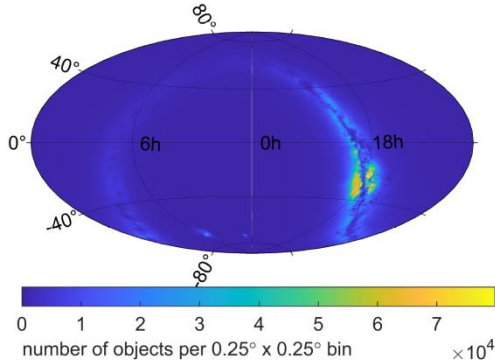
- Multiple radio frequencies

- Operating since 1979

- 2 parameters for [reference frame](#) objects (positions), 5 parameters possible

Official products

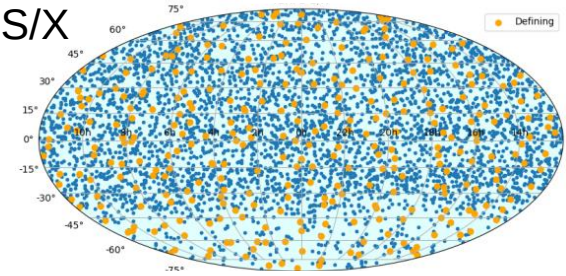
EDR3 data release
published on 03.12.20



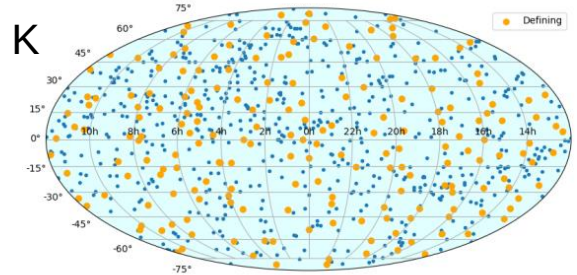
catalog	Number of objects
Gaia EDR3	1.8 billion
ICRF3 S/X	4536
common	3142

- ICRF3 is the latest realization of the **ICRS**
- Gaia EDR3 is oriented towards ICRF3 using **2007 suitable** out of the 3142 counterparts¹.

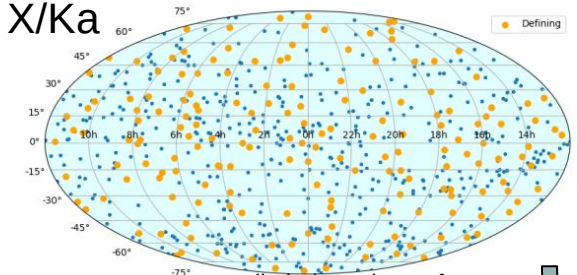
ICRF3 S/X



ICRF3 K



ICRF3 X/Ka



credit: hpiers.obspm.fr

ICRS and ICRF

- **International Celestial Reference System** (ICRS) is an ideal reference system used for astrometric purposes
- The ICRS and the International Terrestrial Reference System (ITRS) are connected by Earth Orientation Parameters (EOP)
- The realization of ICRS is the **International Celestial Reference Frame** (ICRF)
- The ICRF is realized by **Very Long Baseline Interferometry** (VLBI) observations of extragalactic objects which are emitting signals detectable at radio frequencies
- For geodesy, the **extragalactic objects ideally have a point-like emission** in the plane orthogonal to the line of sight (this reduces systematic errors)
- Its origin is the **barycenter of the solar system**, the pole and right ascension origin are fixed to extragalactic radio sources within $\pm 20 \mu\text{as}$.¹



Magnitude dependence of alignment

- Gaia dataset has optical magnitude limits of about $3 \text{ mag} < G < 21 \text{ mag}$
- No matched ICRF3 radio source is brighter $G < 13 \text{ mag}$
- Rotation of the optically bright sources cannot be verified by ICRF3 directly
- The Gaia internal calibration for the bright sources is independent from the calibration for the faint ones
- Rotation of the **bright frame** towards ICRF3 **needs additional verification**

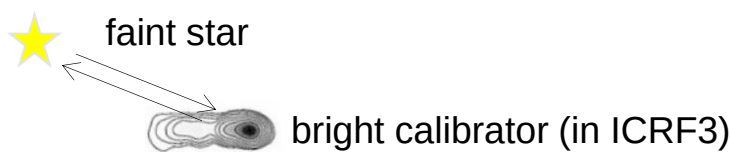
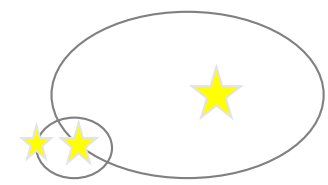
Expected final Gaia error (De Bruijne et al. 2014):

G [mag]	3–12.09	13
σ_0 [μas]	5.0	7.7
σ_ϖ [μas]	6.7	10.3
σ_μ [$\mu\text{as yr}^{-1}$]	3.5	5.4

→ comparison to Hipparcos
limited to $600 \mu\text{as}$ (orientation)
and $25 \mu\text{as/yr}$ (spin) per axis
→ only VLBI will be precise
enough



VLBI observations

- **VLBI data archive** for stars is sparse in time and sky distribution in terms of suitable continuum astrometric observations
 - stars are **not in ICRF3** (absolute geodetic **VLBI positions** from group delay observable which is used for CRF/ TRF/ EOP creation)
 - **stars are 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:
- 
- **physical nature of stars** not easy to account for: radio-optical offsets, high variability, multiple star systems (orbital motion, acceleration terms).
- 



Rotation of the Gaia bright frame

Frame rotation with respect to ICRF3: $\varepsilon(t) = \varepsilon(T) + (t - T) \cdot \omega$
instantaneous configuration (orientation) ε and angular velocity (spin) ω
→ Least squares fit, details see Lindegren (2020a)

Input:

- VLBI: absolute position at epoch t **and/or** proper motion, parallax
- Gaia: position, proper motion and parallax at epoch T propagated to VLBI epoch t, radial velocity from SIMBAD database

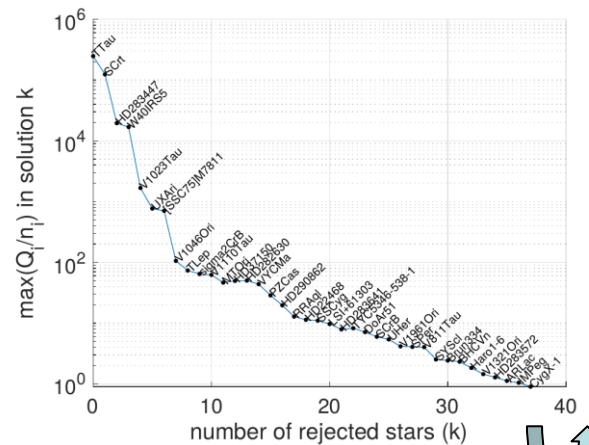
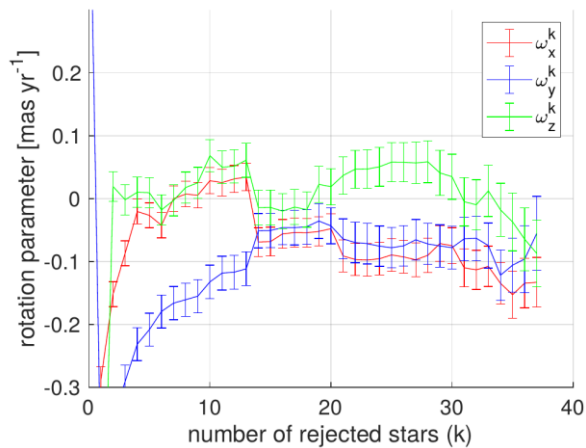
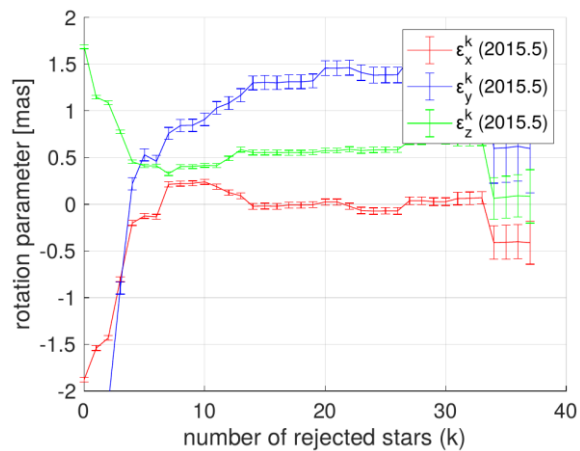
Output:

- ε and ω that need to be applied to Gaia data
- adjusted parameters for VLBI (e.g. 2 VLBI positions inserted results in weighted mean position)

Important: positions are used for the adjustment of orientation **and** spin, proper motions are used for adjustment of spin

Status of literature

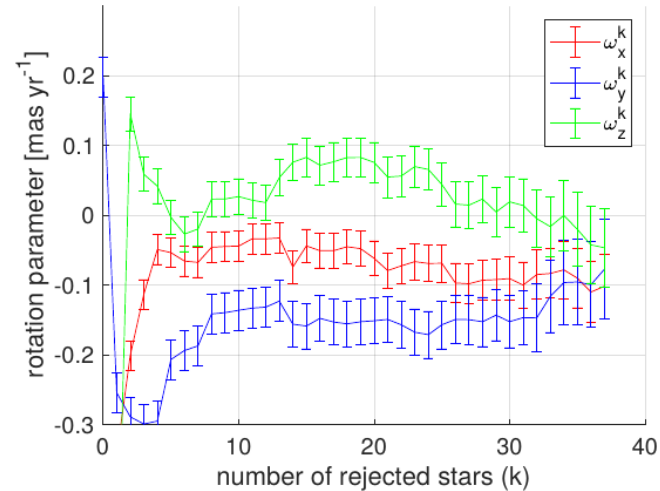
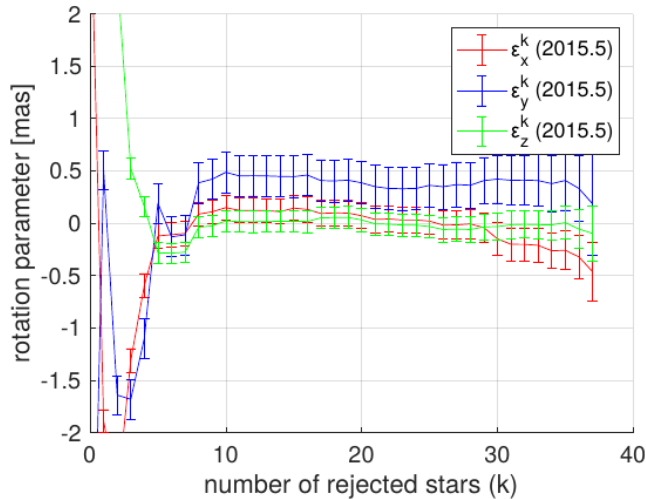
- Original analysis and data collection from Lindegren (2020a), towards Gaia DR2
- Several iterations, rejected star k is most discrepant source in the previous adjustment iteration (where $\max\left(\frac{Q_i}{n_i}\right)$ is similar to the reduced χ^2 of the source*)
- Significant rotation found between **Gaia DR2** and **ICRF3**
 → evaluation of the analysis with Gaia DR2 and results for Gaia EDR3 in this study



* In each of the solutions in the following slides, a different order of rejected stars is possible!

Homogenized data from literature

- Same data as before, but homogenized by referencing all star positions to ICRF3 and by accounting for ICRF3 calibrator catalog position uncertainties for all star position uncertainties

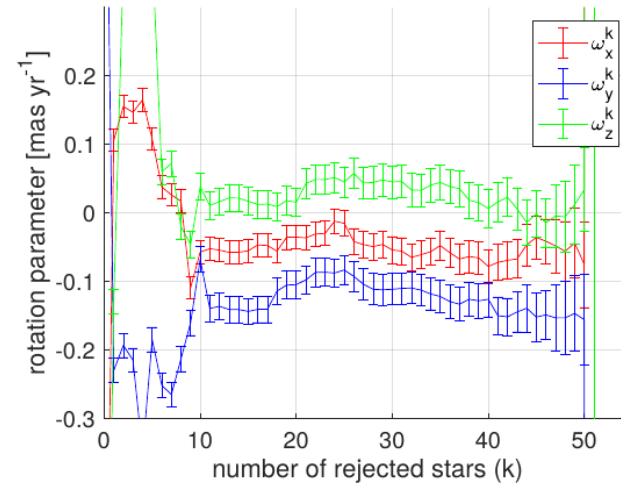
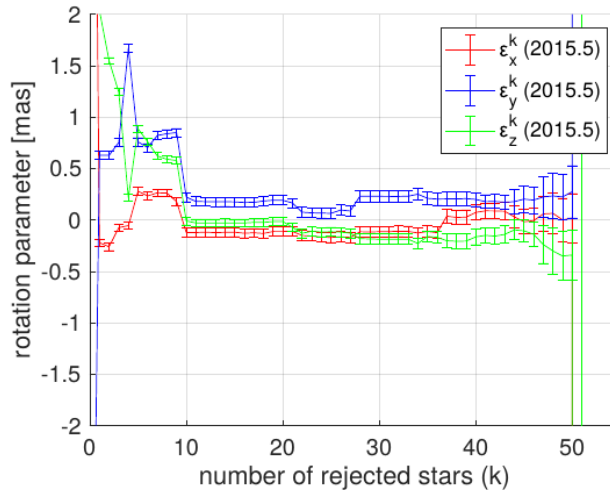


Added new one-epoch observations

- Added new one-epoch positions for 32 well distributed stars across the sky from dedicated observations with the Very Large Baseline Array (VLBA) in January 2020
- Lower formal errors due to more data
- Correlations between parameters disappear

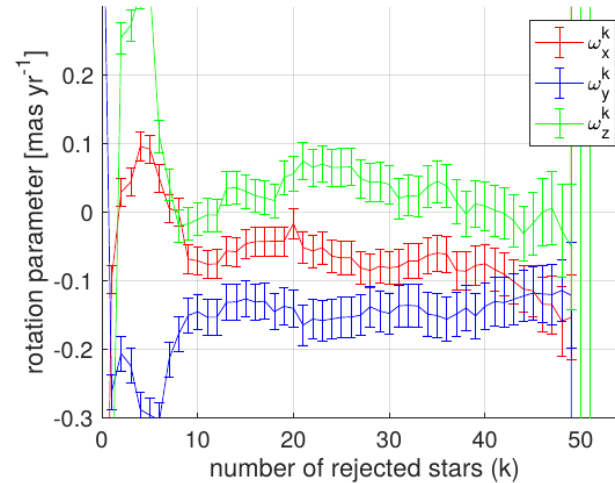
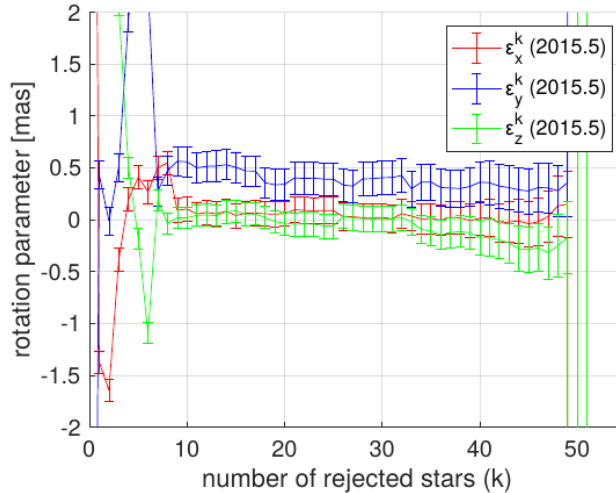


The VLBA network.
Credit: NRAO/AUI/NSF



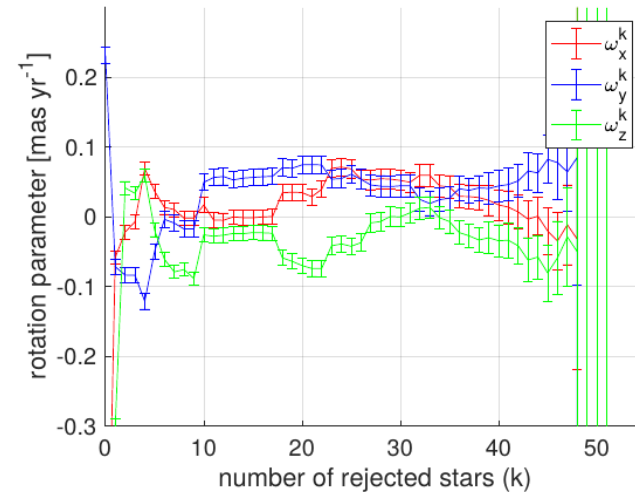
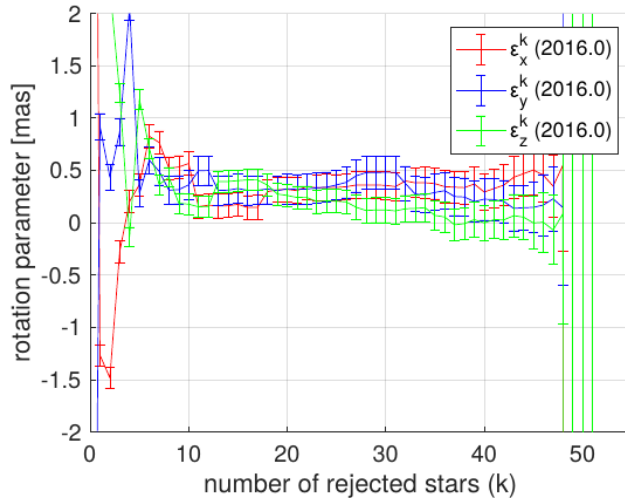
Realistic error assessment

- Increased star position error budgets in order to account for residual tropospheric and ionospheric gradients between the calibrator and the star, antenna position errors, inaccurate earth orientation, [calibrator source structure](#), and the difference between group- and phase-delay positions in the presence of core shift



Results for Gaia EDR3

- In Gaia EDR3 the spin of the bright frame was corrected to be zero towards the Hipparcos frame, which is aligned to ICRS at epoch J1991.25 within 0.6 mas (Lindgren 2020b) → **residual** spin determined



Galactic aberration (GA)

- Galactic aberration is the effect of the centripetal acceleration of the Solar System Barycenter in the orbit around the Galactic center, which shows up as a **systematic dipole effect** in the VLBI positions of extragalactic sources of about 5 $\mu\text{as/yr}$ in direction of the Galactic center
- **ICRF3** is the first realization of ICRS which accounts for galactic aberration.
- Intrinsic systematics in **Gaia EDR3** are small enough to detect the effect (Gaia Collaboration 2020a)
- **Historic phase-referencing data** does not account for this systematics in calibrator positions → systematic effect on **positions and proper motions** of the phase-referenced stars

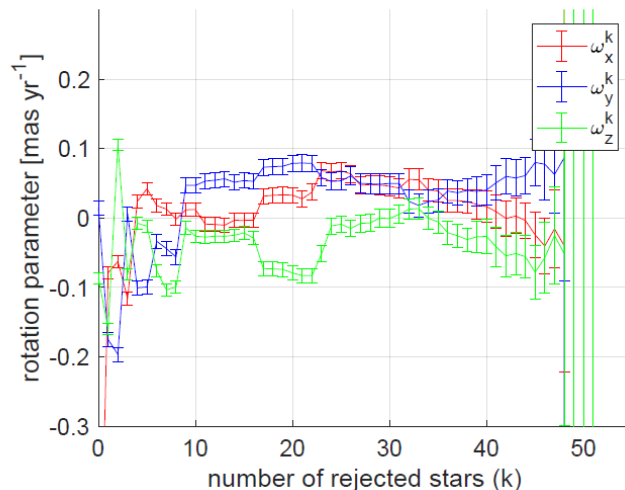
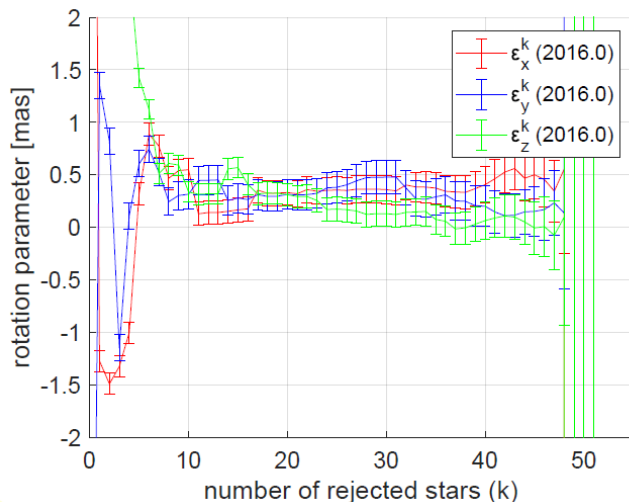
[Click here
for results](#)



Results for Gaia EDR3 incl. GA

→ **residual** spin determined

- included corrections for Galactic aberration in the VLBI radio star data
- Effect is negligible on the rotation parameter analysis with the existing VLBI results



What does this mean for the user?

- We believe the most realistic iteration is the one with $k=13$ rejected stars:

parameter	ε_X [mas]	ε_Y [mas]	ε_Z [mas]	ω_X [mas/yr]	ω_Y [mas/yr]	ω_Z [mas/yr]
value	0.142	0.452	0.321	-0.010	0.057	-0.026
σ	0.112	0.137	0.099	0.010	0.011	0.009

These frame rotations are **larger** than the Gaia EDR3 mean position uncertainties of 0.01-0.02 mas for $G < 15$ mag and the proper motion uncertainties of 0.02-0.03 mas/yr for $G < 15$ mag (cosmos.esa.int/web/gaia/earlyedr3).

- They have to be considered when comparing the Gaia absolute positions **to other data in ICRS**
- They have to be considered when comparing the Gaia bright frame positions **to Gaia faint frame positions**
- The **significant spin will result in position offsets** of $>1.1 \pm 0.1$ mas after 10 years



Conclusions

- It is important that all VLBI data are referenced to the same CRF (ICRF3)
- New one-epoch positions have almost no effect on spin determination **if uncertainties are considered realistically**
- VLBI provides about **twice as accurate spin parameters** than method used during Gaia EDR3 processing
- Although spin was already corrected during Gaia EDR3 processing **still significant spin is present**
 - > **Gaia EDR3 bright frame will deviate from ICRF with time**
 - > **Gaia EDR3 bright frame will deviate from Gaia EDR3 faint frame with time**
- **Rotations** are still larger than expected final Gaia error from De Bruijne et al. (2014)
- Some counterparts show large influence on the rotation parameters which can be identified from “jumps” found in the analysis when rejecting the star
- **More accurate and precise proper motion** information is needed in order to better identify outlier counterparts and to improve the reliability of the results
- In contrast, the influence of correct handling of Galactic aberration is negligible with the existing VLBI results



In case of questions ...

- Ask me in the chat
- Post a comment
- Write an email to susanne.lunz@gfz-potsdam.de
- The work is submitted to A&A → stay tuned

Thank you very much!

Acknowledgements

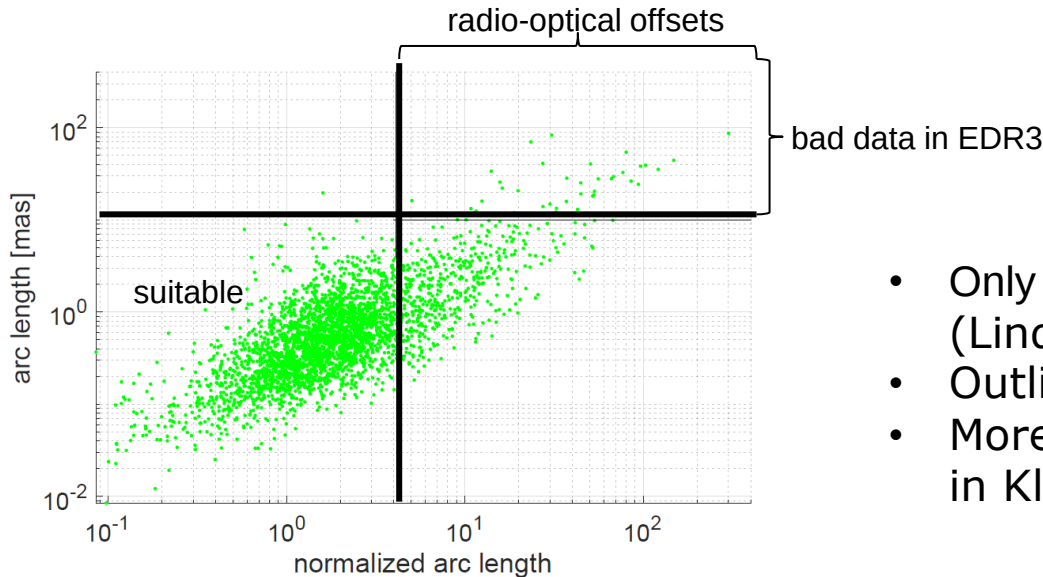
The authors acknowledge use of the Very Long Baseline Array under the US Naval Observatory's time allocation. This work supports USNO's ongoing research into the celestial reference frame and geodesy. We thank also the Socorro correlator for reliably and quickly providing the correlated data. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc..

This project is supported by the DFG grants No. SCHU 1103/7-2 and No. HE 5937/2-2. M. H. Xu was supported by the Academy of Finland project No. 315721.

This work has made use of the data from the European Space Agency (ESA) mission Gaia processed by the Gaia Data Processing and Analysis Consortium as well as from the mission Hipparcos. Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. Calibrators were selected using the NRAO VLBA calibrator search tool (www.vlba.nrao.edu/astro/calib/), the RFC calibrator search tool (astrogeo.org/calib/search.html) and the Astrogeo VLBI FITS image database (astrogeo.org/vlbi_images/). This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France and the SIMBAD database, operated at CDS, Strasbourg, France. Calculations were made in MATLAB by The MathWorks, Inc.

Counterparts

- Radio-optical position offsets (= arc length) for Gaia EDR3 and ICRF3 S/X vs. normalized arc length (arc length divided by the full 2x2 covariance matrix (Mignard et al. 2016))



- Only 5-parameter solutions selected (Lindgren et al. 2020)
- Outliers were excluded¹
- More information to be published in Klioner et al. (2020, A&A in prep.)

