International Celestial Reference System and Frame (ICRS/ICRF)

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Celestial Reference Systems

- A **Celestial Reference System** is a physical reference system that is used to describe coordinates of celestial bodies
- Depending on the celestial bodies there are different **celestial reference systems**:
  - Extragalactic reference system (other galaxies)
  - Galactic reference system (our galaxy>: “Milky Way”)
  - Solar system ephemerides (Sun, planets, moons, planetoids, asteroids, etc.)
  - Satellite orbits or satellite constellations (GNSS space segments, LAGEOS orbits, etc.)
- The extragalactic system is the **conventional celestial reference system** [1] (CCRS), i.e. the other CRS use it for external orientation, i.e. as a datum
- The CCRS is **realized** by **VLBI** (Very Long Baseline Interferometry), which is a space geodetic technique of operational technology readiness level
- Through VLBI the CCRS is **maintainable** as long as VLBI observations are acquired

1: IAU / IUGG Working Group MERIT, Wilkins & Mueller (1986)

Celestial Reference Systems (cont.)

- Restriction: the **CCRS** is only **quasi-inertial**, i.e. its non-rotation is not a physical characteristic, it is achieved through mathematical constraints (NNR functions of celestial coordinates): "**kinematically non-rotating**"
  → depending on the choice of datum points, the orientation might differ a bit (this effect is about at the level of 20 – 30 μas for ICRF3)
- **Ring lasers, (quantum) gyroscopes** and comparable inertial sensors realize **dynamically non-rotating reference systems**, but these sensors depend on local environmental effects that degrade their mid- and long-term stability
- The **accessibility** is another important feature of the CCRS
  - The VLBI-realized CRS is global. It can be accessed from everywhere on Earth and in the solar system at any time through observation of its objects.
  - Local inertial sensors are not globally accessible. They display local rotational characteristics.

International Celestial Reference System: ICRS [1]

Origin: Solar System Barycenter (SSB)

Metric, “scale”: Barycentric Coordinate Time: TCB (French: temps-coordonnée barycentrique), BCRS [2]

Orientation:
Principal plain ($\delta = 0$): true celestial equator at epoch J2000.0 given through the precession (IAU 1976) and nutation (IAU 1980) models

Origin of right ascension ($\alpha = 0$):
Ascending intersection point (♈) between the equatorial and the mean ecliptical plains

P_0: celestial pole at J2000.0

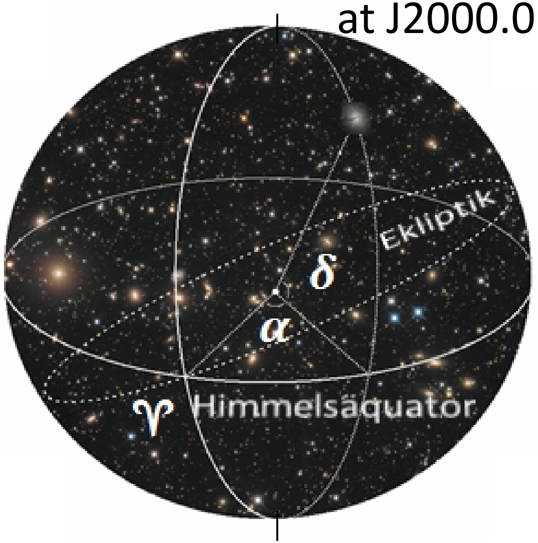


Fig.: ICRS (schematic)

1: Arias et al. (1995) *Astron. Astrophys.* 303, 604—608
2: IAU Res. B1.3 (2000) http://www.iau.org/static/resolutions/IAU2000_French.pdf#page=5

Extragalactic radio sources

- **ICRF = realization of the ICRS** through a sufficient number of coordinate pairs (α, δ) of extragalactic radio sources determined by geodetic / astrometric analysis of VLBI observations
- An **extragalactic radio source** is associated with a shock region of a relativistic jet of an active galaxy, the shock region is not entirely compact ("point-like", source structure) and can vary with time: time-dependent core shift
- The shock region is frequency stratified with higher frequencies closer to the galactic center [(2)]: frequency-dependent core shift

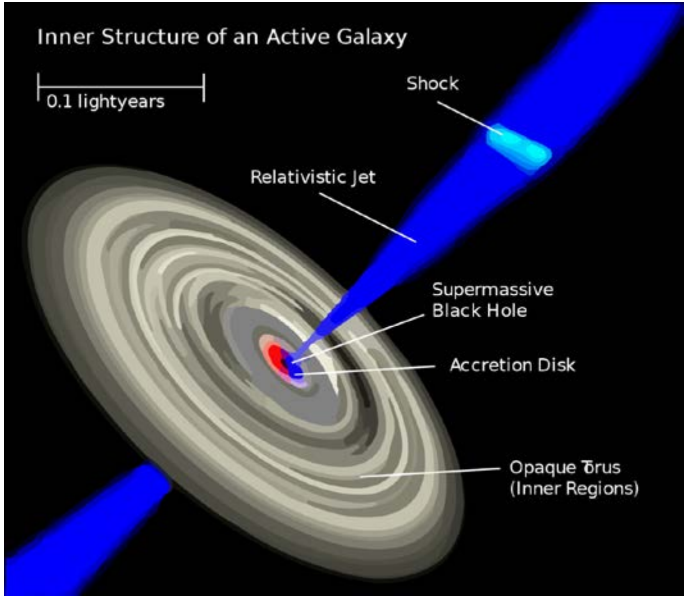


Fig.: center of an active galaxy [(1)]

1: Rothwild (2016) @ en.wikipedia.org/wiki/Active_galactic_nucleus
2: Wehrle et al. (2009) in Astro2010 "Galaxies Across Cosmic Time", 2009astro2010S.310W

Astrometry of extragalactic radio sources

- **Structure** of radio sources obtained from visibility-based **radio images**

- Alternatively, **closure quantities** can be utilized. This topic is research done at GFZ [1]

Structure of radio source 4C39.25 during 15 years

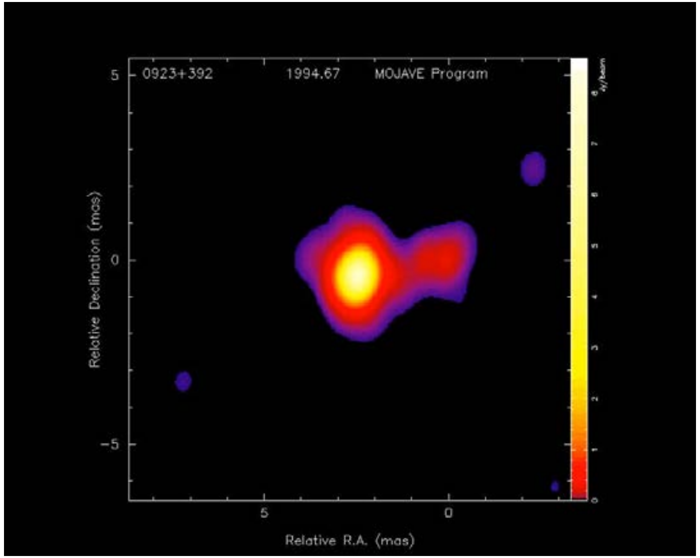


Fig. from MOJAVE program (Purdue Univ.)

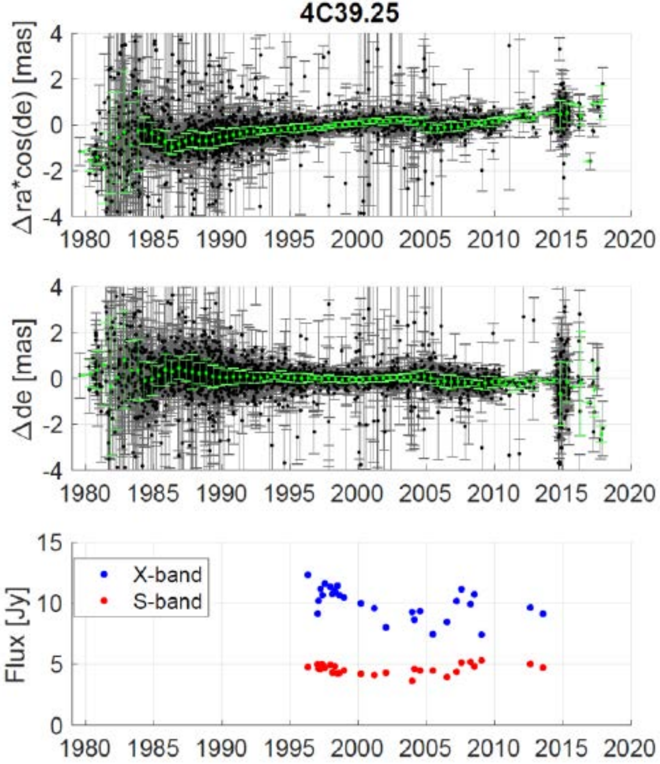


Fig. from S. Lunz (GFZ)

1: Xu, Heinkelmann, Anderson et al. (2016) Astron. J. 10.3847/0004-6256/152/5/151
Xu, Heinkelmann, Anderson et al. (2017) J. Geod. 10.1007/s00190-016-0990-x

Radio Reference Frame history

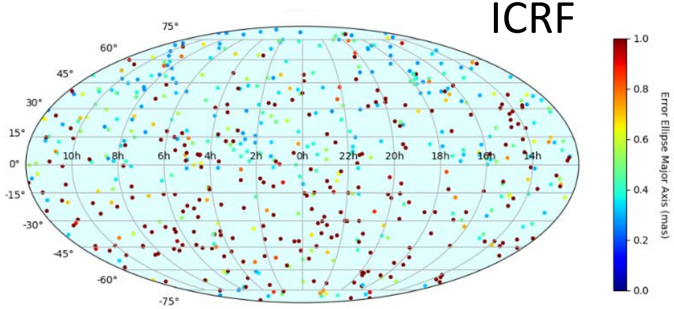
< 1977 More than 50 different radio source catalogues with about 30,000 objects [1]

1991 The IERS extragalactic Celestial Reference Frame and its tie to HIPPARCOS [2]

1997 Definition and realization of the ICRS by VLBI astrometry of extragalactic objects [3]

1998 ICRF [4] 212 defining
294 candidate
102 others

ICRF



1999 ICRF-Ext.1 [5] 59 new

2004 ICRF-Ext.2 [6] 50 new

717 total

Adopted re-definition of the CCRS

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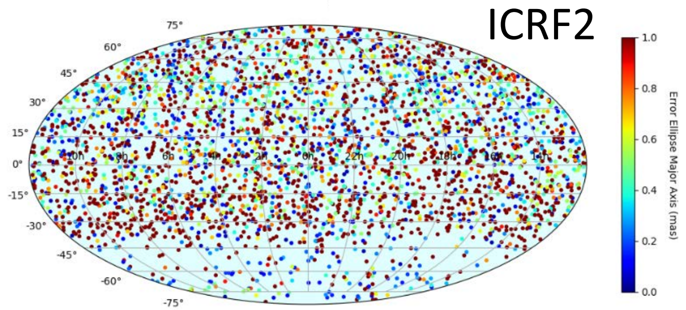
1: Kesteven & Bridle (1977), 1977JRASC..71...21K 2: IERS TN 7 (1991) 3: IERS TN 23 (1997)
4: Ma et al. (1998), 1998AJ....116..516M 5: IERS AR 1999 6: Fey et al. (2004)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Radio Reference Frame history (cont.)

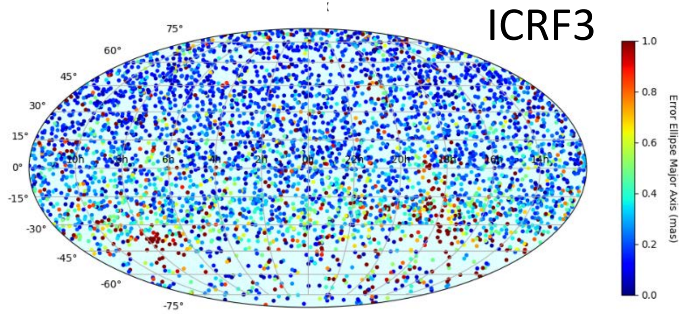
2010 ICRF2 [1]

295 defining
39 special handling
1114 candidate
1966 survey
3414 total



2019 ICRF3 [2]

303 defining
4233 candidates
4536 total



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1: Fey et al. (2015), 2015AJ....150...58F
2: Charlot et al. (in prep.), *Astron. & Astrophys.*

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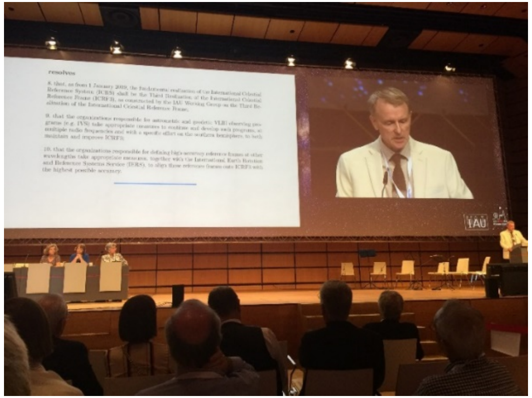
The current realization: ICRF3

- ICRF3 was created by the **IAU Division A WG** „Third realization of the International Celestial Reference System: ICRF3” between 2012 and 2018
- It was adopted at the IAU General Assembly 2018 AUG in Vienna, Austria, univocally in terms of **IAU Resolution B2 (2018)** (1)
- It was adopted at the IUGG General Assembly 2019 JUL in Montreal, Canada, through **IAG Resolution 2 (2019)** (2)



1: https://www.iau.org/static/resolutions/IAU2018_ResolB2_English.pdf
2: https://iag.dgfi.tum.de/fileadmin/IAG-docs/IAG_Resolutions_2019.pdf

ICRF3 datasets

- ICRF3 includes solutions at **three different radio bands**: X/S, K and Ka/X-bands

IVS

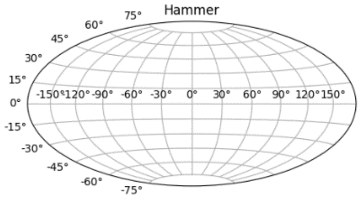
VLBA

DSN + ESA

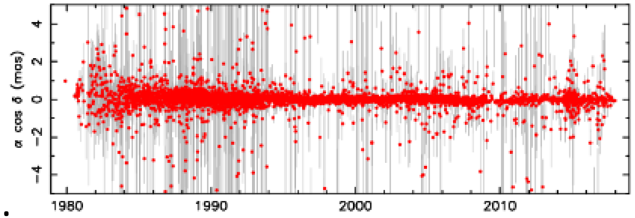
Band	Frequency (GHz)	Nb of obs. (millions)	Fraction of observations (%)					Data span
			IVS	VLBA	Ht-Ho	DSN	ESA	
X/S	8.4 / 2.3	13.2	74	26				1979-2018
K	24	0.5		99	1			2002-2018
Ka/X	32 / 8.4	0.07				87	13	2005-2018

ICRF3 defining sources selection

Separation of the celestial sphere into **324 sectors of equal area**

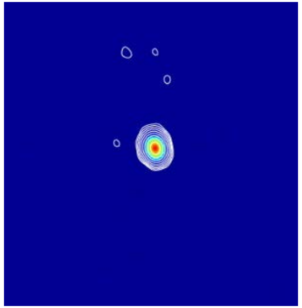


Ordering the sources populating a sector by their **astrometric quality**



Categorization due to structure (size, variability, SI) into three groups:

- A „very good or excellent“
- B „with extended structure“
- C „poor structure“



Identification of the **most stable and compact radio source of each sector**

ICRF3 defining sources

216 sectors with a **class A** radio source	**72%**
62 sectors with a **class B** radio source	**20%**
19 sectors with **only class C** radio sources	**not considered**
25 sectors **without images** (no class assigned)	**8%**
2 sectors **without any radio source**	**<1%**
total	**303 defining sources**

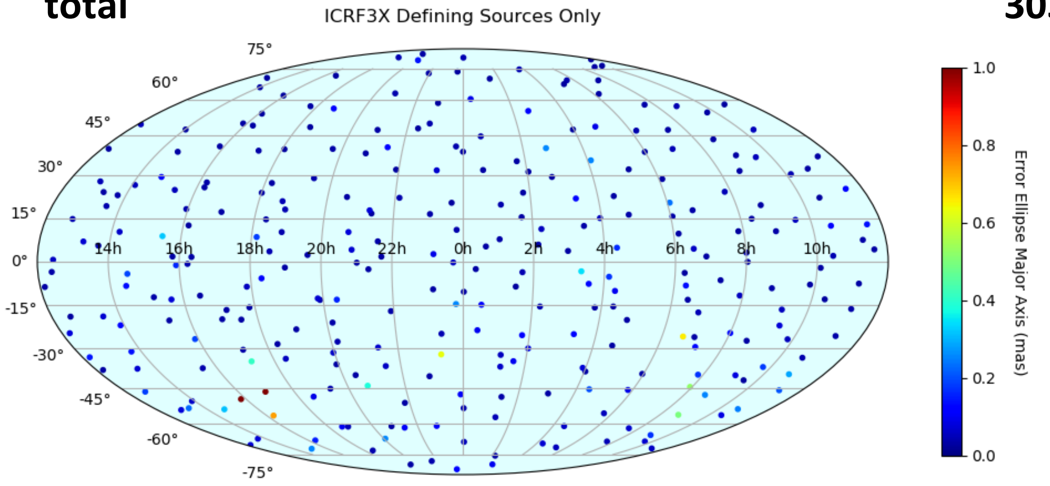


Fig.: ICRF3 defining sources

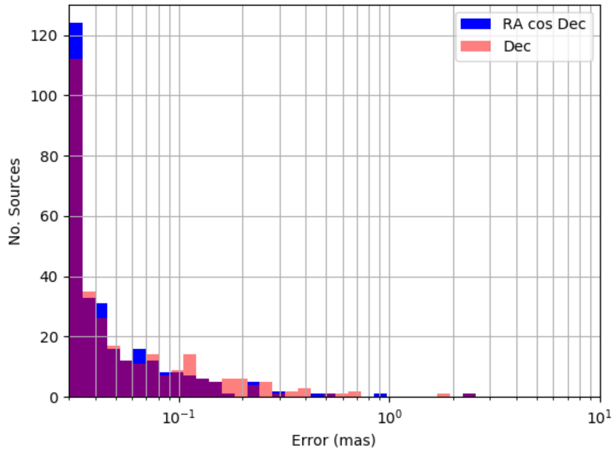


Fig.: repeatability of ICRF3 defining sources

ICRF3 solution configuration

Adhere to IERS Conventions (2010)

Ionospheric corrections for single band (K) were obtained using IGS GIM [(1)]

ICRF3 celestial frame parameterization

- All source coordinates as **global parameters**
- ICRF3-X/S aligned to **ICRF2** (through NNR w.r.t. the 295 defining sources of ICRF2)
- ICRF3-K and ICRF3-Ka/X rotated onto ICRF3-X/S (through common defining sources of ICRF3)

ICRF3 terrestrial frame and EOP

- Station coordinates as **global parameters**
- ICRF3-X/S-TRF aligned to **ITRF2014** (through NNR w.r.t. IVS core network stations)
- **EOP estimated per session**

Formal error „inflation" to account for some of the omitted errors

- Factor 1.5 (for X/S and K) and a constant error of 30 μas (50 μas) added to X/S (Ka/X)

1: https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/atmospheric_products.html#iono

ICRF3 Working Group solutions

ICRF3-X/S prototype solutions provided at 2016 SEP, 2017 JUL, and 2018 JAN

- 2017 JUL solution provided to Gaia Science Team for defining the Gaia DR2 orientation!

X/S band (8.4/2.3 GHz)

- 7 final solutions from IVS [1] ACs: AUS / GFZ / GSFC / IAA / OPA / USNO / VIE
- Using 5 different software packages: Occam / GFZ VLBI sw / Calc/Solve / Quasar / VieVS
- GSFC (Calc/Solve) chosen for ICRF3, others used for comparisons and tests

K band (24 GHz)

- 1 solution: GSFC (Calc/Solve)

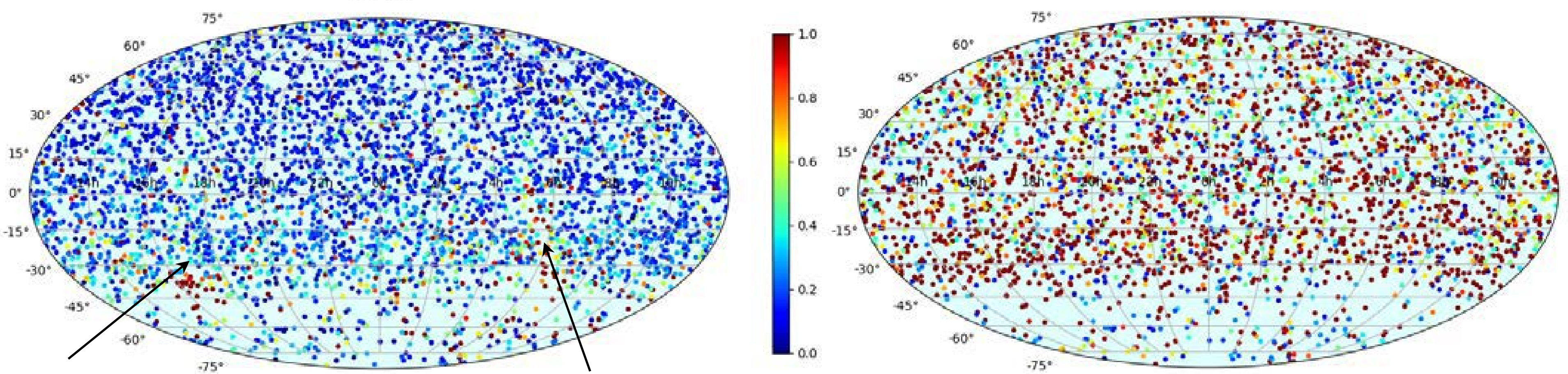
Ka/X band (32/8.4 GHz)

- 1 solution: JPL (Modest)

1: https://ivscc.gsfc.nasa.gov/

ICRF3 – ICRF2 comparison

	ICRF3-X/S	ICRF2 (X/S only)
categories	defining, rest	defining, special handling, rest, survey (VCS)
number of objects	303, 4233	295, 39, 1114, 1966
total	**4536 (35% more)**	**3414**



Galactic center

Galactic plain

ICRF3 – ICRF2 comparison

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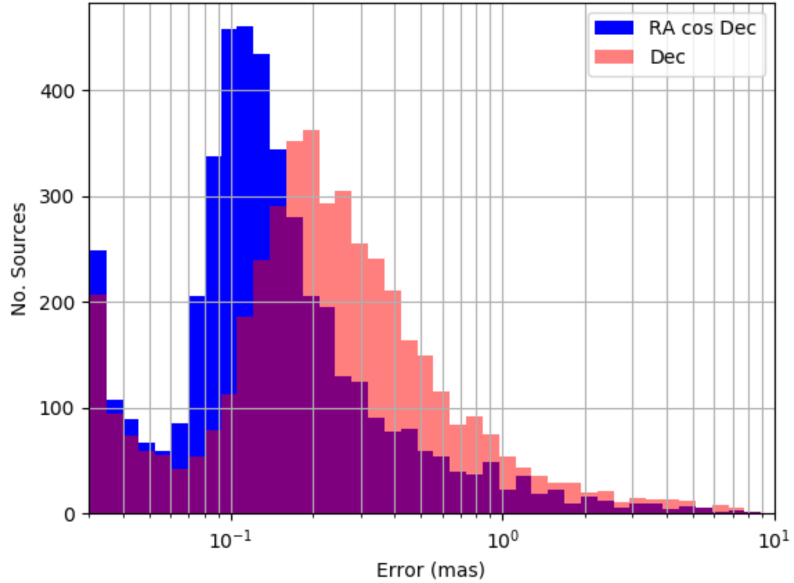
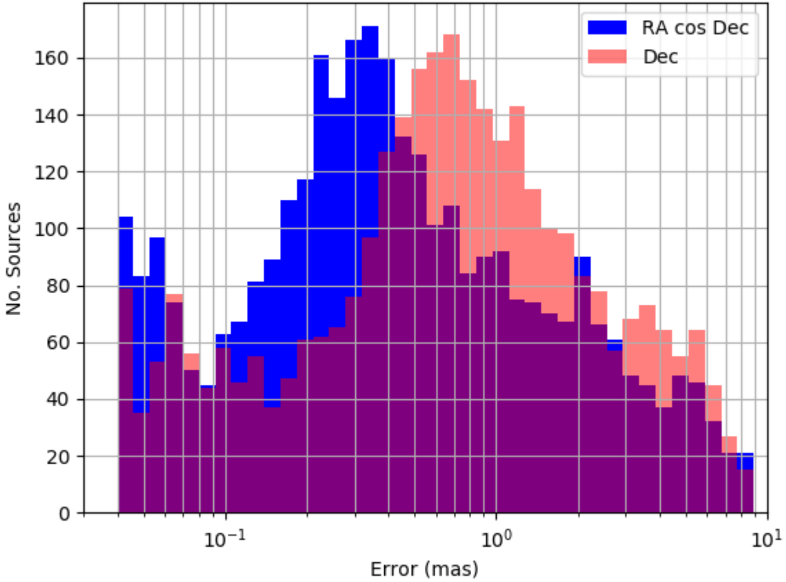
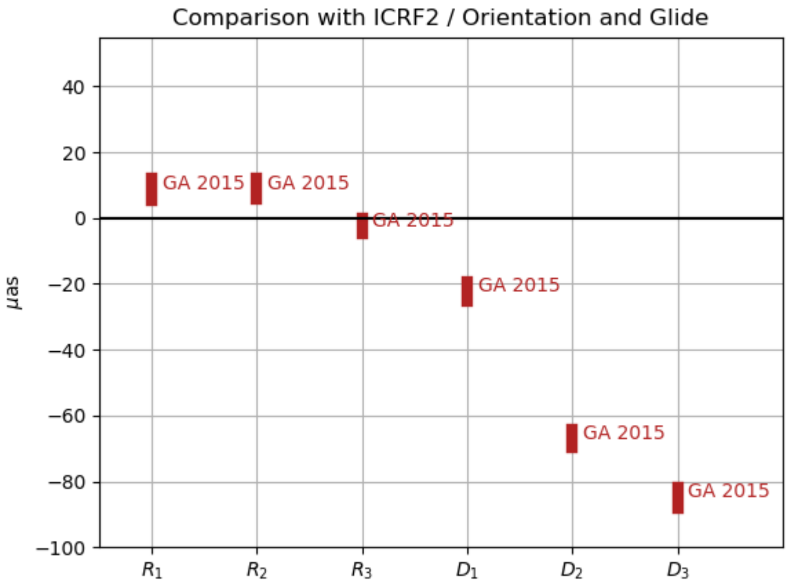
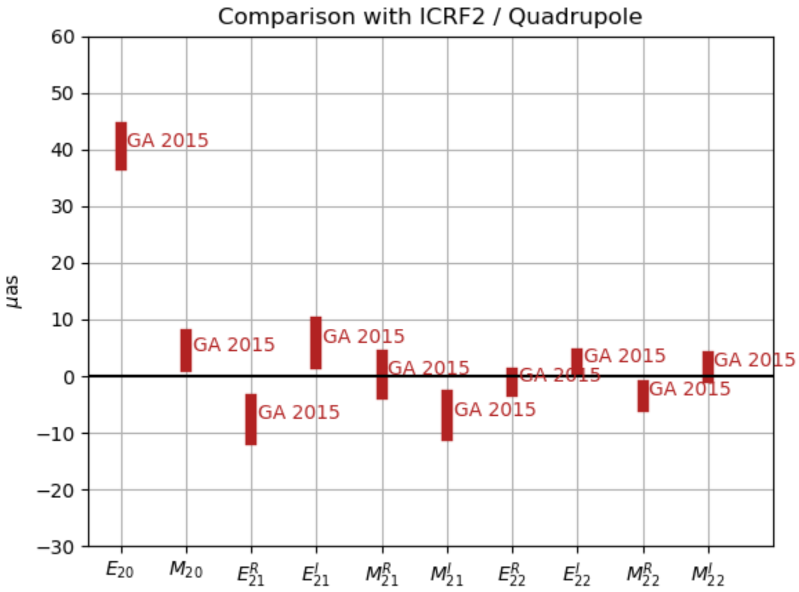




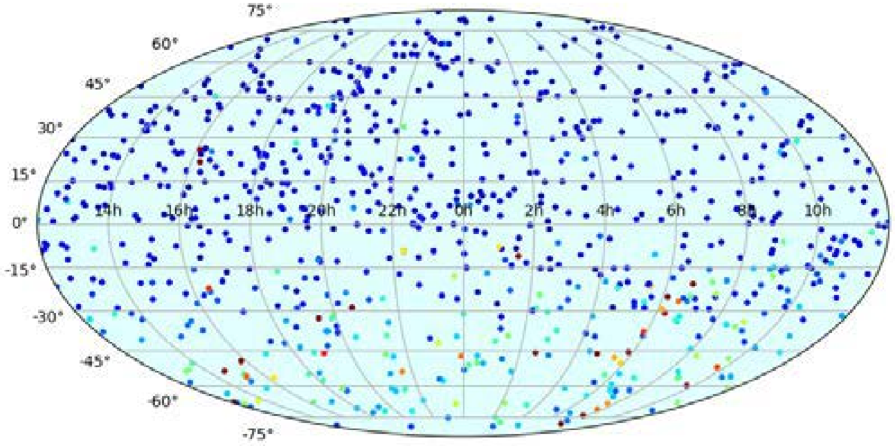
ICRF3 – ICRF2 comparison at 2015.0

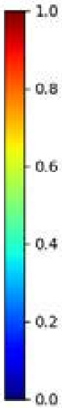


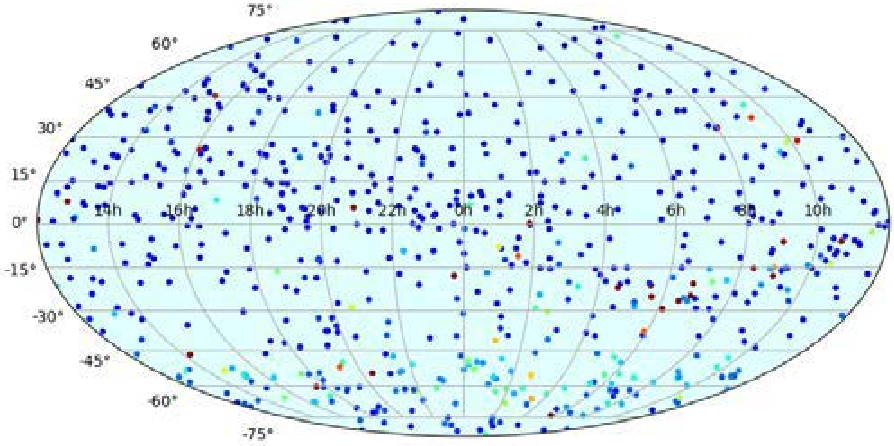


ICRF3 other radio bands

	ICRF3-K	ICRF3-Ka/X
total	**824**	**678**







ICRF3 other radio bands

	ICRF3-K	ICRF3-Ka/X
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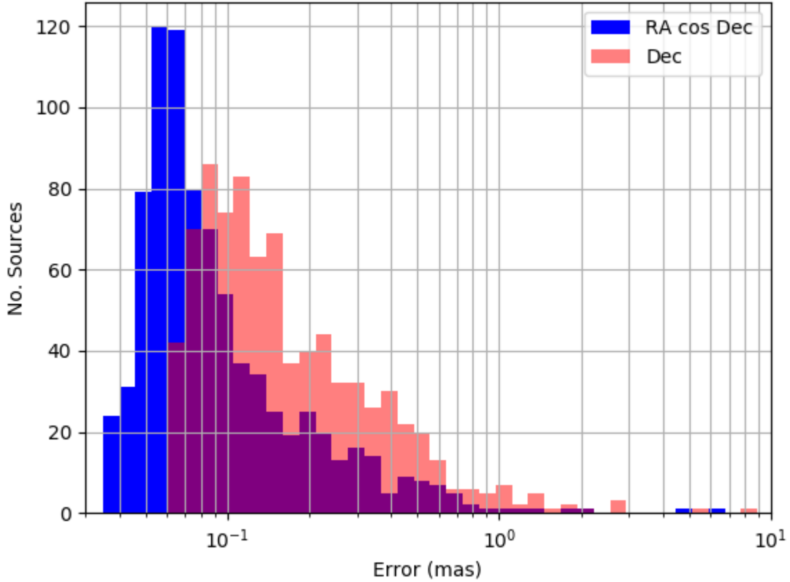
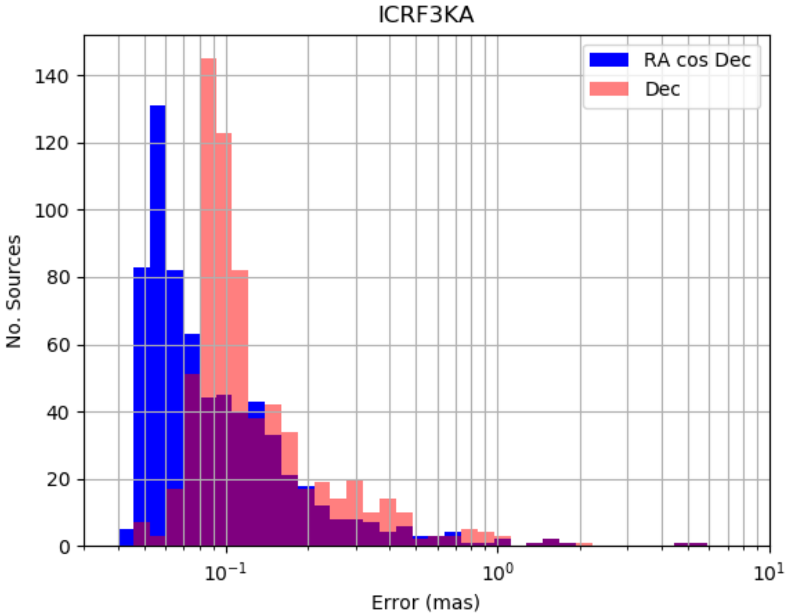




ICRF3 galactic aberration

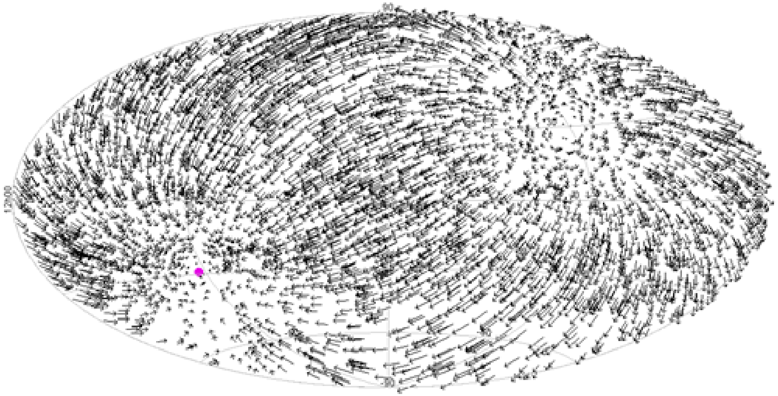
The linear motion of the SSB (≈220 km s^{-1}) is part of the reported coordinates.

De-Sitter precession is negligible:
0.0085 μas yr^{-1} (1)

Aberration is not negligible:
ICRF3 uses VLBI value: 5.8 μas yr^{-1} while fixing the position of the galactic center to IAU values:

$\alpha = 17^h 45^m 40^s$

$\delta = -29° \, 00' \, 28''$



The aberration causes a dipole proper motion field towards the GC

credits: S. Lunz

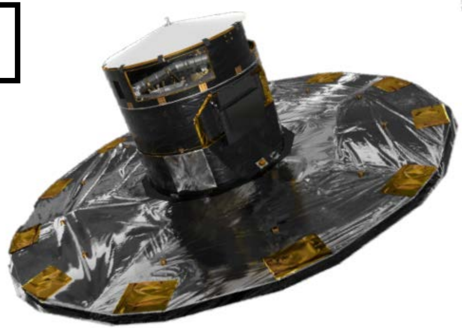
ICRF3 considers the aberration due to rotation of the solar system (SSB) around the galactic center (GC) on the observation level (2) → ICRF3 coordinates refer to epoch 2015.0

1: Kovalevsky (2003) *Astron. Astrophys.* 404, 743
2: Titov (2011) *Astron. Rep.* 55 (1), 91

Astrometry mission Gaia

Gaia (Global Astrometric Interferometer for Astrophysics)

esa **since DEC 2013 for > 5 yr**



Credit: ESA

(1)

Gaia-catalogue (non-inertial)
> 1,000,000,000 star positions
relative precision

astrometry-grid	7 μas @ 10 mag
	26 μas @ 15 mag
	600 μas @ 20 mag

Besides optical objects, almost 600,000 radio sources are observed!

1: https://www.cosmos.esa.int/web/gaia/iow_20120312

Gaia DR2 (optical)

- The comparison of ICRF3 with Gaia (ESA) optical catalogue enables **a unique historical chance** for detection of systematic errors of the VLBI and of the Gaia catalogues

- Gaia DR1 2014-07-25 – 2015-09-15

- Gaia DR2 available since 2018-04-25 provides **precision comparable** to ICRF3-X/S

- ICRF3-X/S prototype solution was delivered by the IAU WG to the Gaia community for fixation of the absolute orientation and spin degree of freedom of Gaia

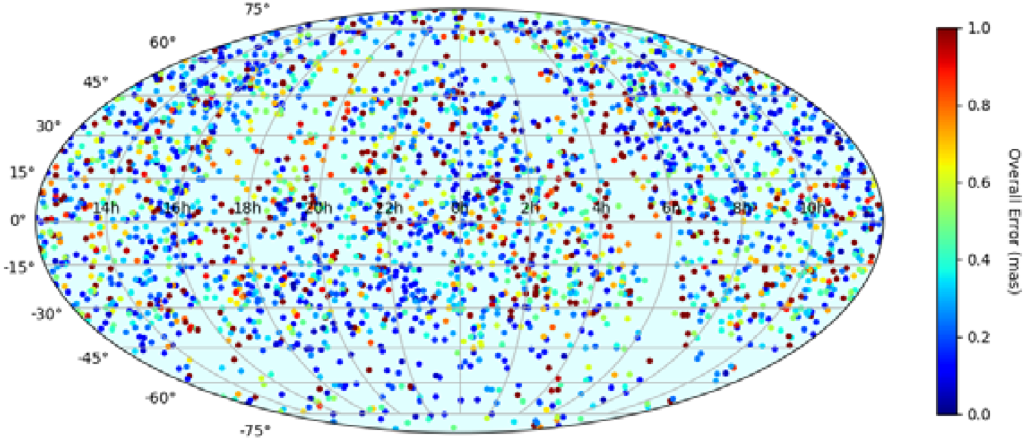
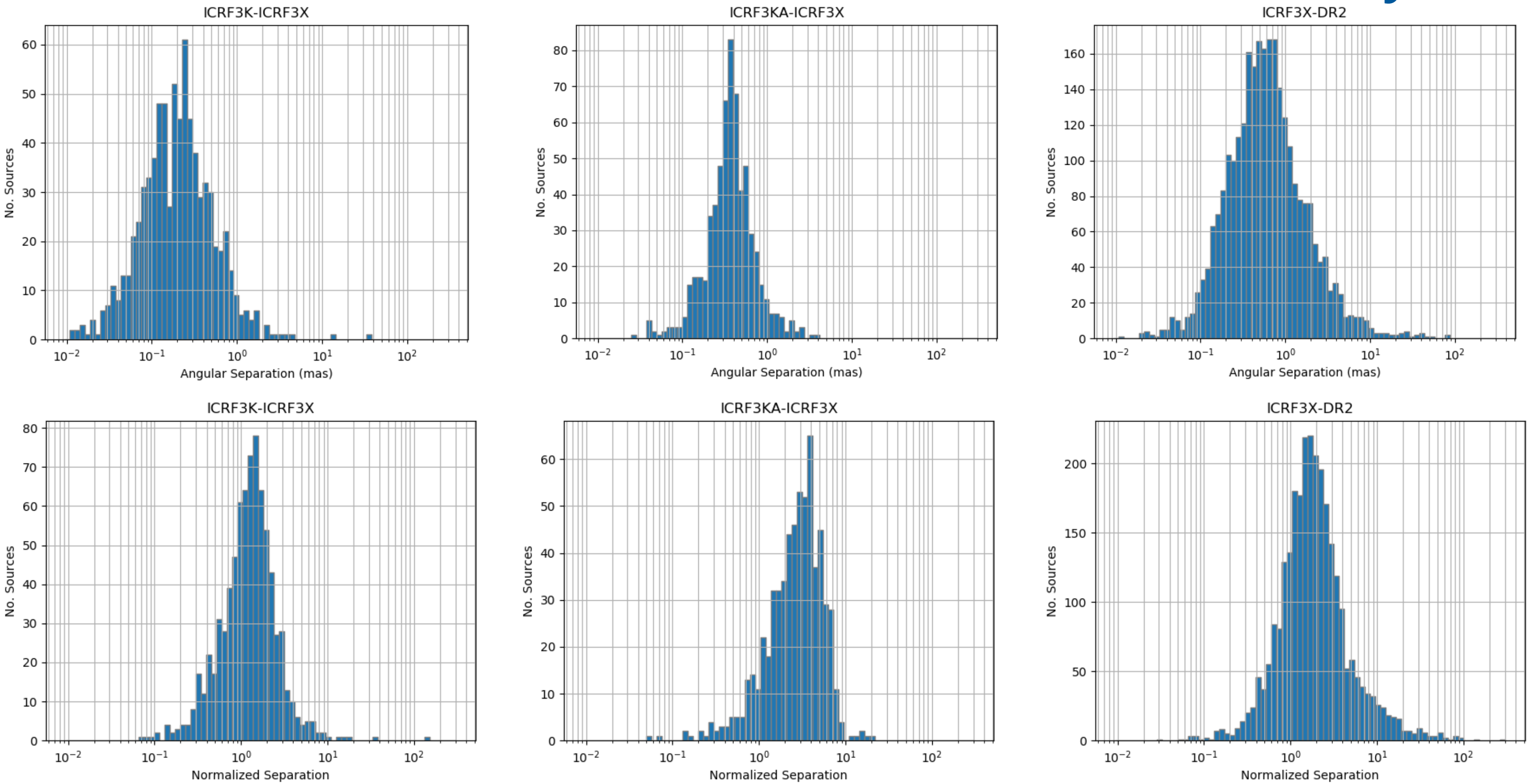


Fig.: Gaia-DR2, no deformation w.r.t. ICRF3 beyond 30 μas

Multi-band ICRF3 and Gaia consistency



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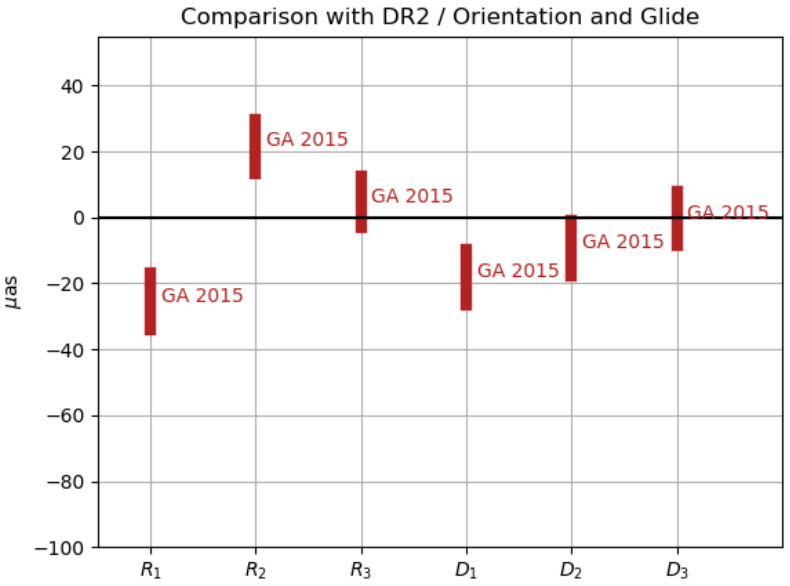
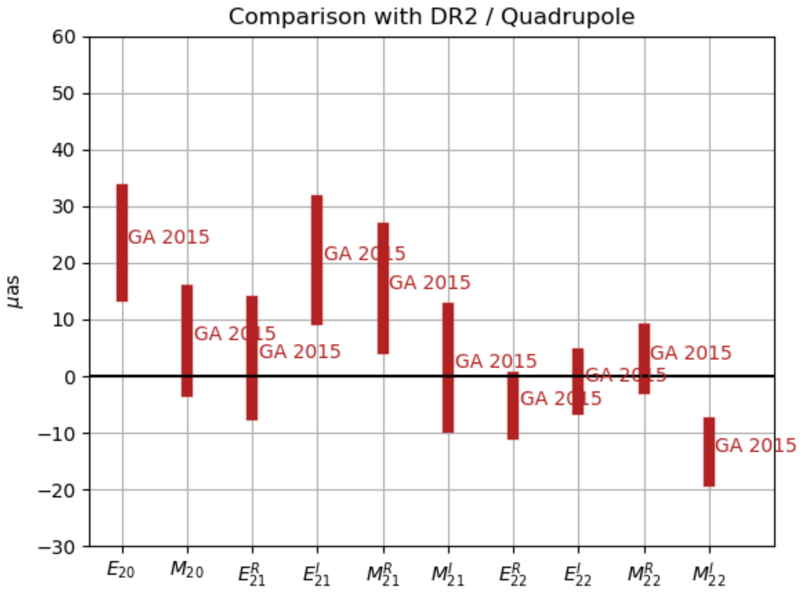
ICRF3 – Gaia DR2 transformation parameters





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ICRF3 – summary

ICRF3 shows significant advance on the observation side

- **Significantly reduced number of single session radio sources** through VCS-II, USNO VLBA campaigns
- **Multi-band agreement is much better than for ICRF2**: K band and Ka/X band w.r.t X/S
- **Deformation (up to 80 μas) vs. ICRF2** detected
- **No deformation (> 30 μas) w.r.t. Gaia DR2**

- **Galactic aberration corrected** (max. proper motion about 5.8 μas yr^{-1})

- **Median position error improved by a factor of 3.5** (vs. ICRF2)

- 3 radio frequency positions for ~600 radio sources

Acknowledgement: several figures and some statistics were taken from presentations of C. Jacobs and P. Charlot held on behalf of the ICRF3 WG

Outlook: personal comments

ICRF4

- **What role will Gaia play for future ICRF?**

- **The faint part of Gaia catalogue (> 13 mag) is very well oriented because of the radio sources that are part of ICRF3**
- **The bright part of Gaia catalogue (< 13 mag) could need improvement in terms of orientation and spin, e.g. through VLBI observations of radio stars**

Thank you for attention!

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Celestial coordinate transformation model 1

$$\begin{aligned}\Delta\alpha &= A_1 \tan\delta\cos\alpha + a_2 \tan\delta\sin\alpha - A_3 + D_\alpha\delta \\ \Delta\delta &= -A - 1\sin\alpha + A_2\cos\alpha + D_\delta\delta + B_\delta\end{aligned}$$

IERS AR (1996)

Celestial coordinate transformation model 2

$$
\begin{aligned}
\Delta\alpha\cos\delta &= R_1\cos\alpha\sin\delta + R_2\sin\alpha\sin\delta - R_3\cos\delta - D_1\sin\alpha + D_2\cos\alpha \\
&+ a_{20}^{M}\sin 2\delta \\
&+ \left(a_{21}^{E,\mathrm{Re}}\sin\alpha + a_{21}^{E,\mathrm{Im}}\cos\alpha\right)\sin\delta \\
&- \left(a_{21}^{M,\mathrm{Re}}\cos\alpha - a_{21}^{M,\mathrm{Im}}\sin\alpha\right)\cos 2\delta \\
&- 2\left(a_{22}^{E,\mathrm{Re}}\sin 2\alpha + a_{22}^{E,\mathrm{Im}}\cos 2\alpha\right)\cos\delta \\
&- \left(a_{22}^{M,\mathrm{Re}}\cos 2\alpha - a_{22}^{M,\mathrm{Im}}\sin 2\alpha\right)\sin 2\delta, \\
\Delta\delta &= -R_1\sin\alpha + R_2\cos\alpha - D_1\cos\alpha\sin\delta - D_2\sin\alpha\sin\delta + D_3\cos\delta \\
&+ a_{20}^{E}\sin 2\delta \\
&- \left(a_{21}^{E,\mathrm{Re}}\cos\alpha - a_{21}^{E,\mathrm{Im}}\sin\alpha\right)\cos 2\delta \\
&- \left(a_{21}^{M,\mathrm{Re}}\sin\alpha + a_{21}^{M,\mathrm{Im}}\cos\alpha\right)\sin\delta \\
&- \left(a_{22}^{E,\mathrm{Re}}\cos 2\alpha - a_{22}^{E,\mathrm{Im}}\sin 2\alpha\right)\sin 2\delta \\
&+ 2\left(a_{22}^{M,\mathrm{Re}}\sin 2\alpha + a_{22}^{M,\mathrm{Im}}\cos 2\alpha\right)\cos\delta
\end{aligned}
$$

Mignard & Klioner (2012) A&A