The Third Realization of the International Celestial Reference Frame

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ICRF3 Working Group

IAU Working Group formed in 2012 to generate ICRF3 for presentation at IAU 2018 General Assembly

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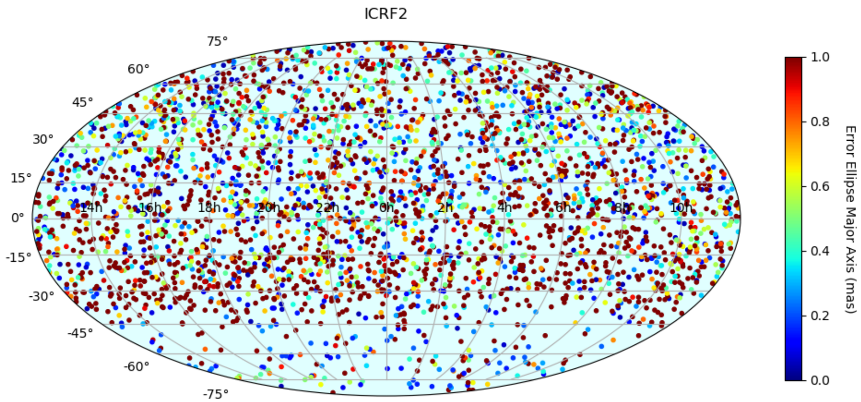
J. Boehm	R. Heinkelmann	E. Skurikhina
S. Bolotin	C. S. Jacobs	J. Souchay
G. Bourda	S. Lambert	O. Titov
A. de Witt	C. Ma	

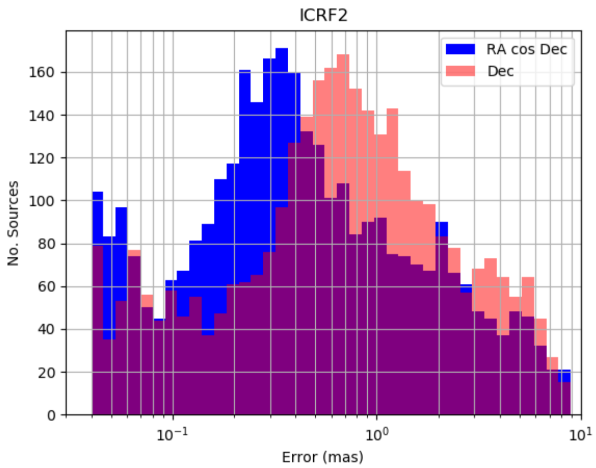
2012-2015: WG chaired by C. S. Jacobs
2015-2018: WG chaired by P. Charlot

Outline

- Background on ICRF2
- Data sets incorporated in ICRF3
- Modeling and analysis configuration
- Overview of ICRF3 and its properties
- Comparison with ICRF2 and Gaia-CRF2
- Consistency of multi-frequency positions
- Release of ICRF3

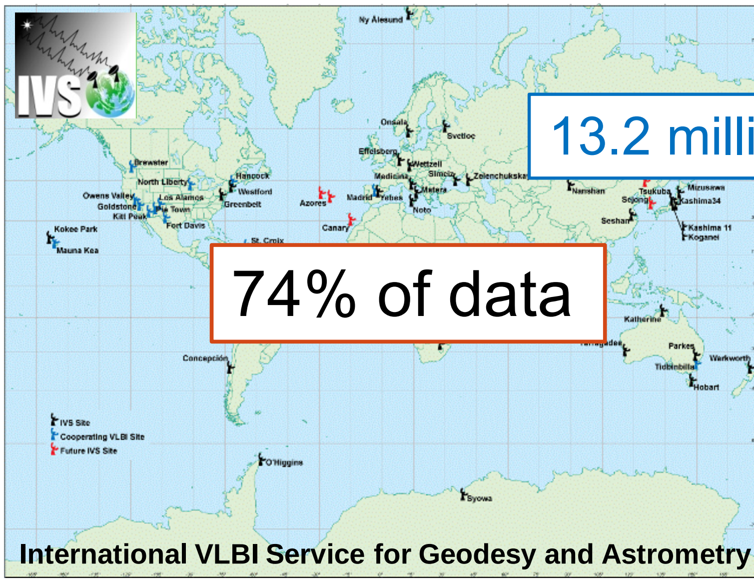
ICRF2





- ICRF2 built in 2009
- Adopted by IAU at XXVIIth General Assembly (Rio de Janeiro, 2009)
- Has 3414 sources, of which 295 are defining sources
- Noise floor in individual source coordinates: 40 µas
- About 2/3 of the sources result from single-epoch survey observations and have much lower position accuracy

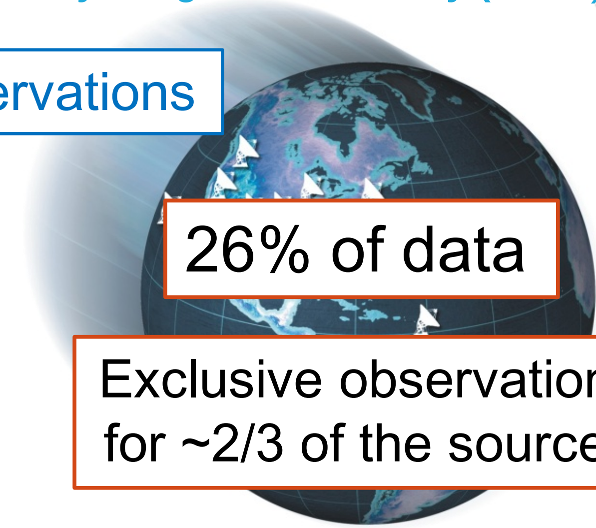
Data sets: S/X band (2.3/8.4 GHz)



13.2 million observations

74% of data

Very Long Baseline Array (VLBA)



26% of data

Exclusive observations for ~2/3 of the sources

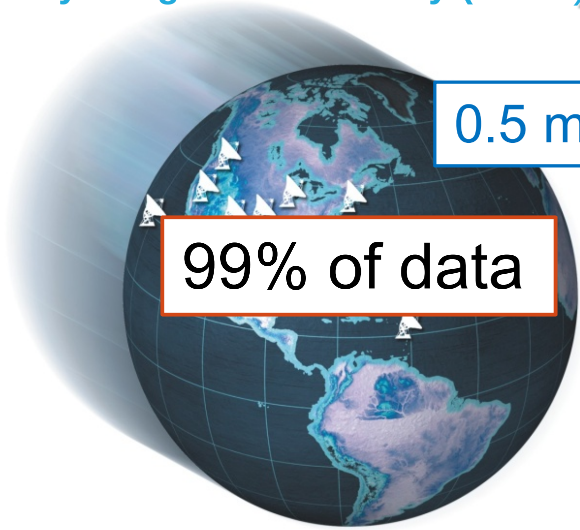
- 6206 sessions incorporating 2 to 20 IVS telescopes (1979-2018)
- 128 sessions also incorporating the 10 VLBA telescopes

- 24 VCS-I sessions* (1994-2007)
- 8 VCS-II sessions (2014-2015)
- 24 additional VCS-type sessions under USNO time (2017-2018)

* VCS=VLBA Calibrator Survey

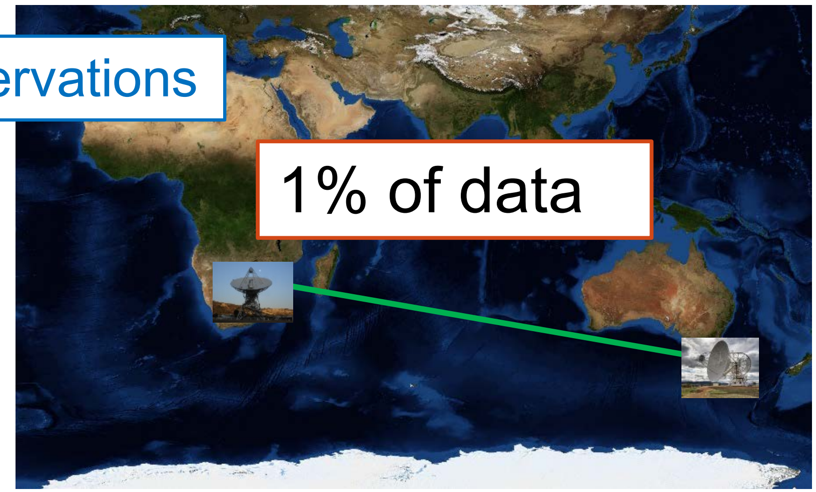
Data sets: K band (24 GHz)

Very Long Baseline Array (VLBA)



0.5 million observations

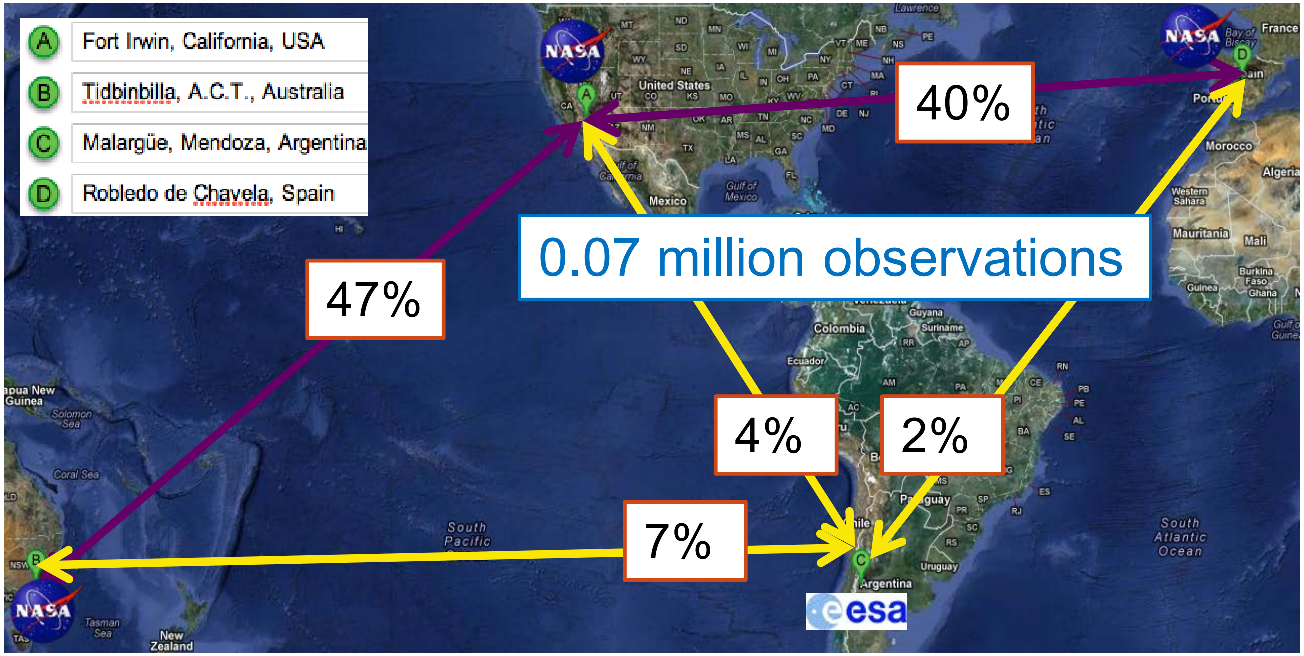
Hartebeesthoek-Hobart observations



- 40 VLBA sessions (2002-2018)
- 16 South-Africa–Australia single-baseline sessions (2014-2018)

Data sets: X/Ka band (8.4/32 GHz)

Deep Space Network + ESA antenna in Argentina



- 167 sessions using DSN antennas and occasionally (~10% of the sessions) the ESA antenna in Malargue (2005-2018)

Overview of analysis work

- Three rounds of ICRF3 prototype solutions accomplished
  - Submitted by 09/2016, 07/2017 and 01/2018
  - 9 solutions (using 6 different software packages) produced each time
  - One such solution provided to the Gaia Science Team in July 2017 to serve as input for defining the orientation of Gaia-CRF2 frame.
- Numerous alternate solutions varying the modeling and analysis configuration to assess the impact on the solutions
  - Cutoff elevation angle, troposphere modeling, station positions
  - Special handling sources, ICRF2-ICRF3 transfer sources
  - Impact of new southern-hemisphere stations in Australia and NZ
  - Treatment of Galactic aberration
- Extensive comparisons between different solutions (also with Gaia DR1 and DR2) essential to identify and resolve issues
- Individual solutions from GSFC adopted for the SX and K band frames and from JPL for the XKa band frame

Modeling and analysis configuration

- Adhere to IERS conventions (2010)
- Ionospheric corrections (K band data) using TEC maps from GPS
- Celestial frame
  - All sources treated as global parameters
  - SX frame aligned onto ICRF2 using the 295 ICRF2 defining sources
  - K and XKa frames aligned onto SX frame using ICRF3 defining sources
- Terrestrial frame and EOP
  - Terrestrial frame aligned onto ITRF2014
  - Station coordinates treated as global parameters
  - EOP estimated per session
- Galactocentric acceleration correction of 5.8 µas/yr applied (estimated from the SX data) – Positions given for epoch 2015.0
- Rescaling of formal position uncertainties
  - Multiplicative factor of 1.5 applied to SX and K band coordinate errors
  - 30 µas added in quadrature to α* and δ errors (50 µas for δ at K band)

EOP consistency

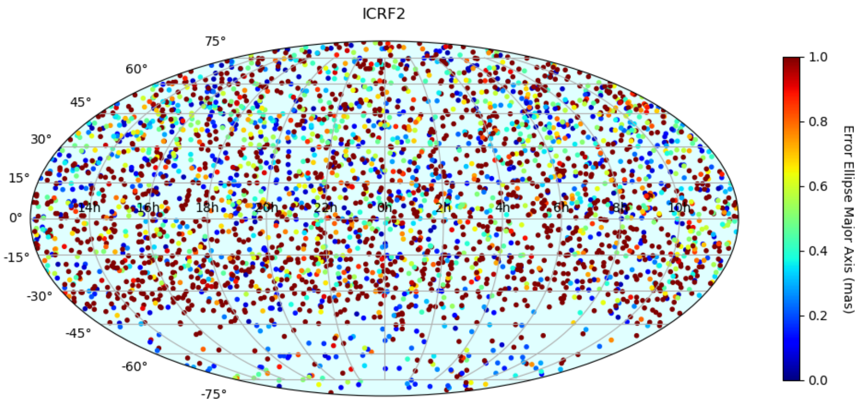
Comparison of the Earth Orientation Parameters estimated as part of the ICRF3 solution with those reported by IVS

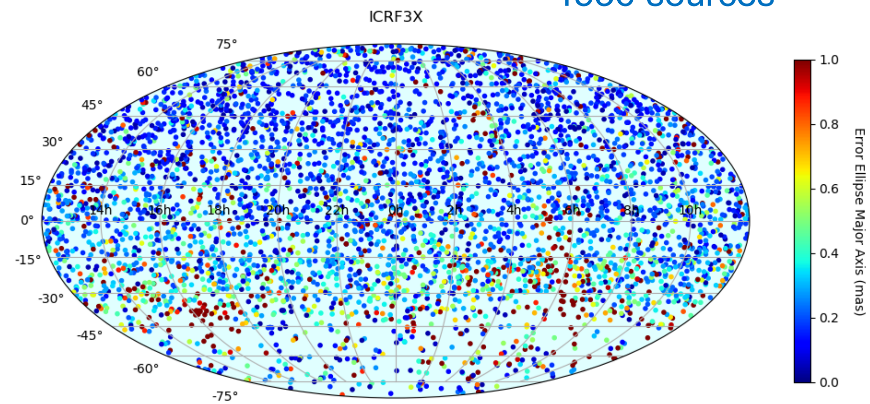
EOP	yp (µas)	yp (µas)	UT1 (µs)	X (µas)	Y (µas)
Median error (ICRF3)	61	56	2.6	55	56
wrms (ICRF3-IVS)	76	79	6.1	45	44
χ^2	2.18	2.43	2.56	1.01	0.98

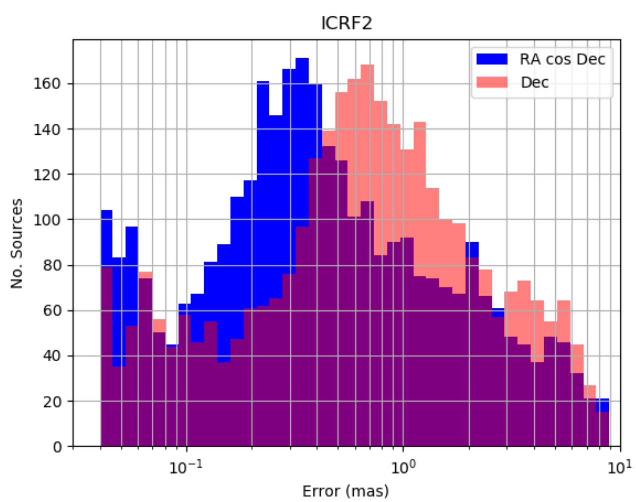
→ Very good consistency with the IVS series

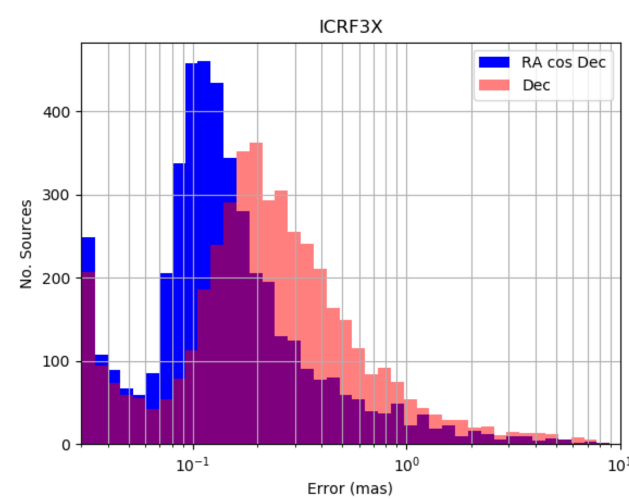
ICRF3-SX

4536 sources



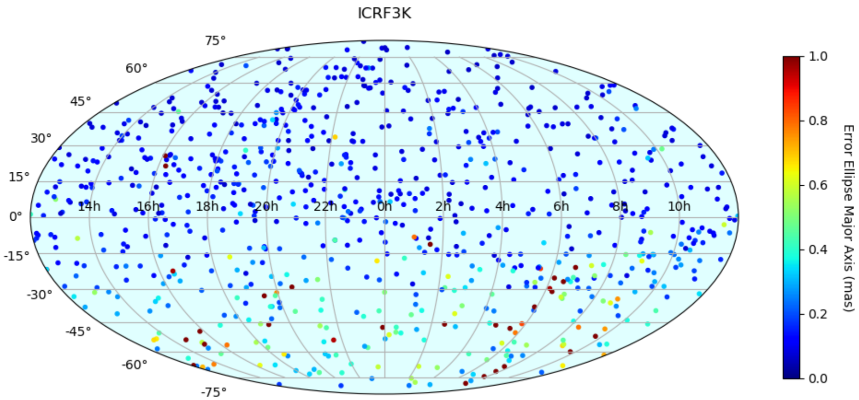




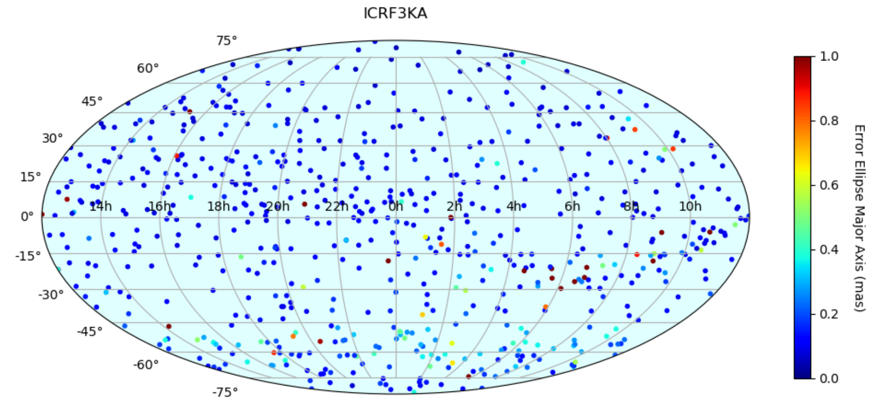


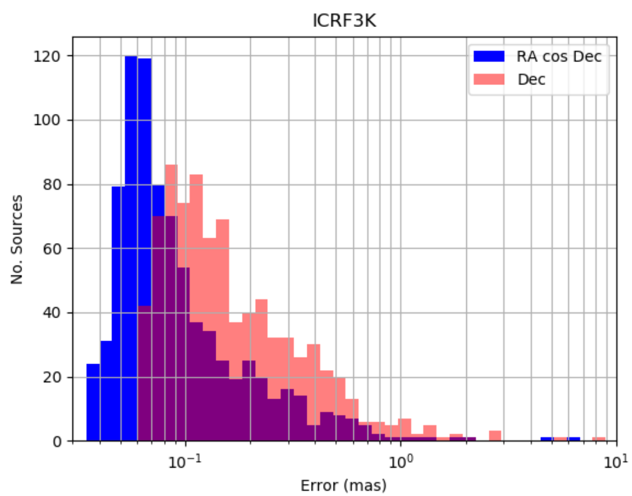
ICRF3-K and ICRF3-XKa

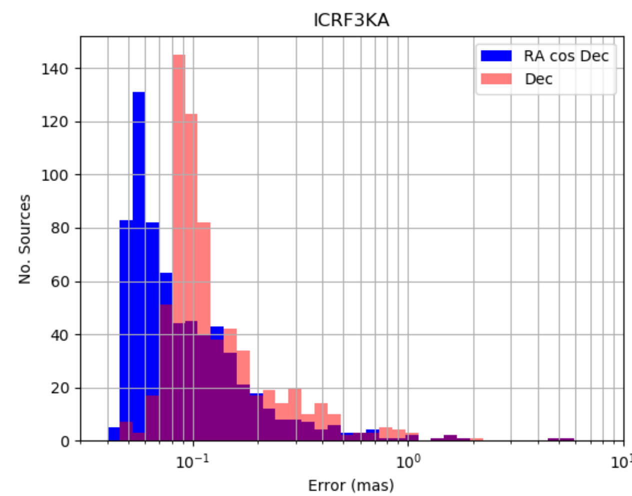
824 sources



678 sources

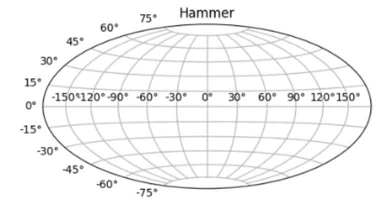




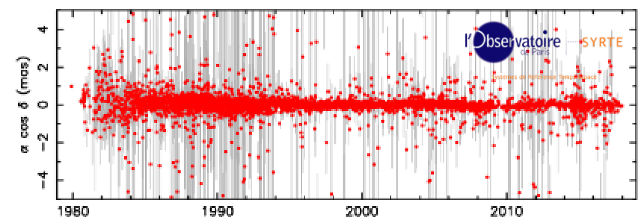


Selection of defining sources

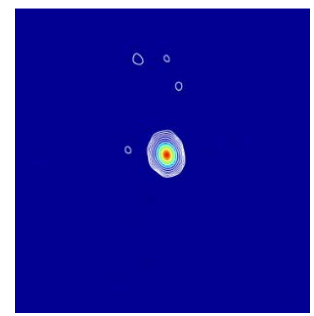
- Sub-divide the celestial sphere into 324 sectors of equal area



- Order sources in each sector according to the quality of the position time series



- Examine VLBI images and categorize sources depending on their structure (size, variability, structure index,..)
  - A = good or excellent
  - B = with extended structure
  - C = poor structure

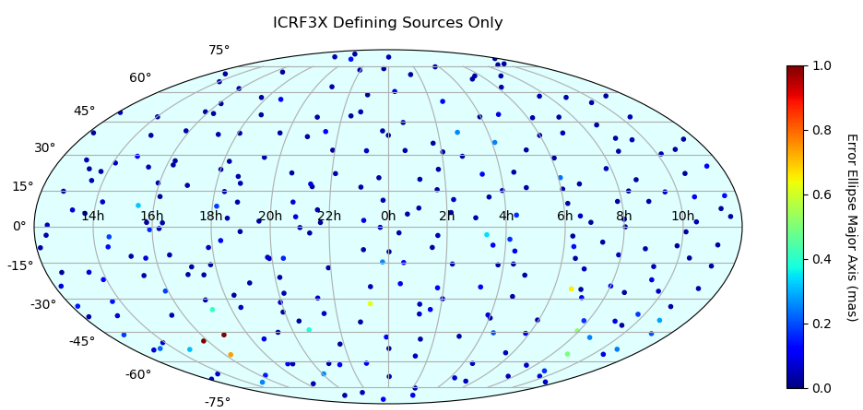


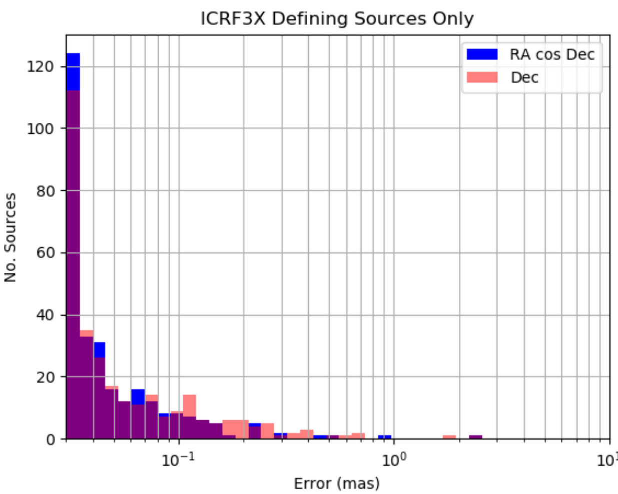
→ Identify the most compact and stable source in each sector and select it as defining source

ICRF3 defining sources

- 216 sectors with a class A source — 72%
- 62 sectors with a class B source — 20%
- 19 sectors with only class C sources — removed
- 25 sectors with structure not assessed (no images) — 8%
- 2 sectors with no ICRF3 source — < 1%

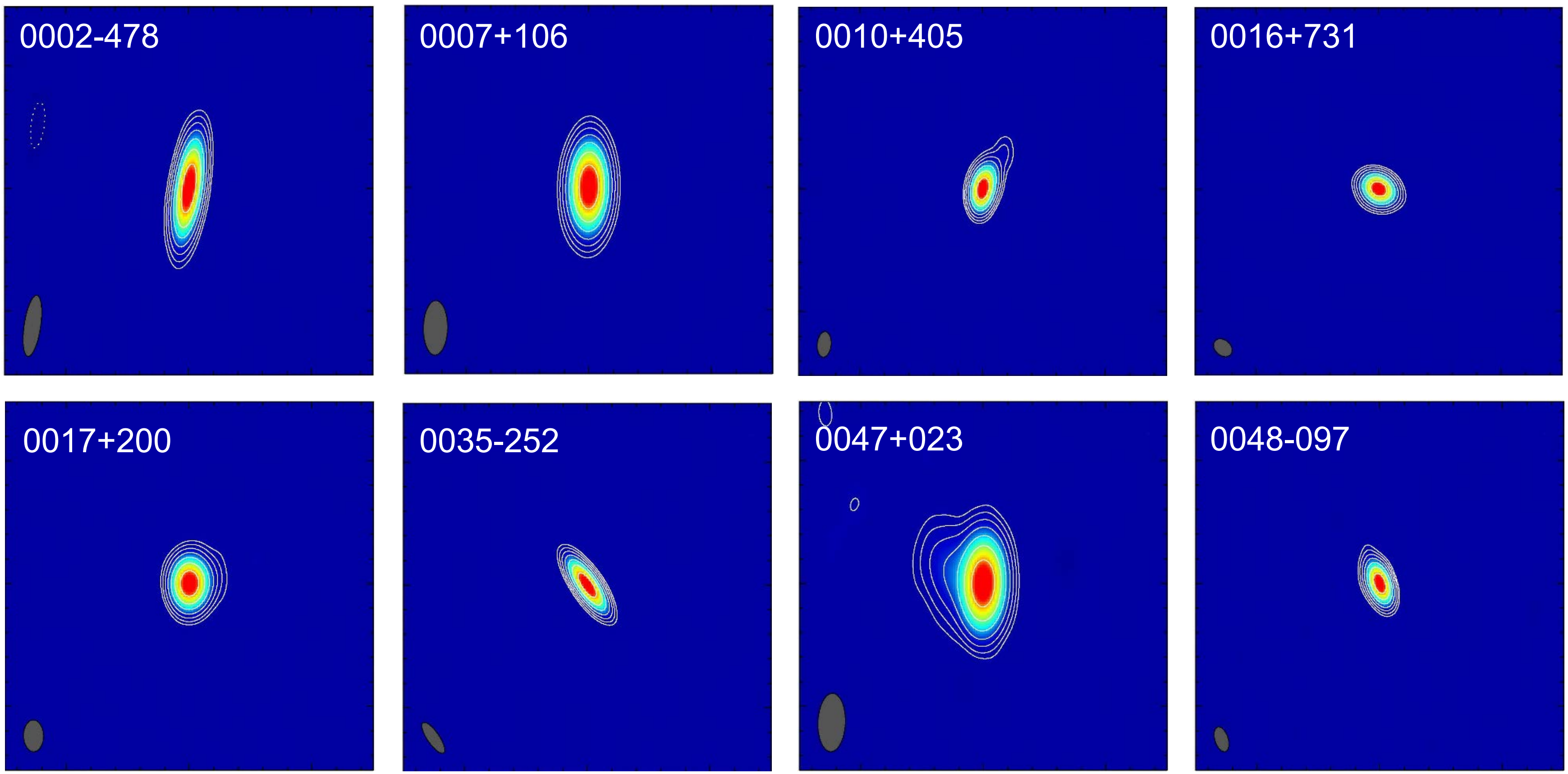
303 defining sources





Some class A defining sources

VLBI images at 8.4 GHz from the Bordeaux VLBI Image Database



Contour levels: ± 1, 2, 4, 8, 16, 32, 64% of peak brightness

Image size: 15 x 15 mas

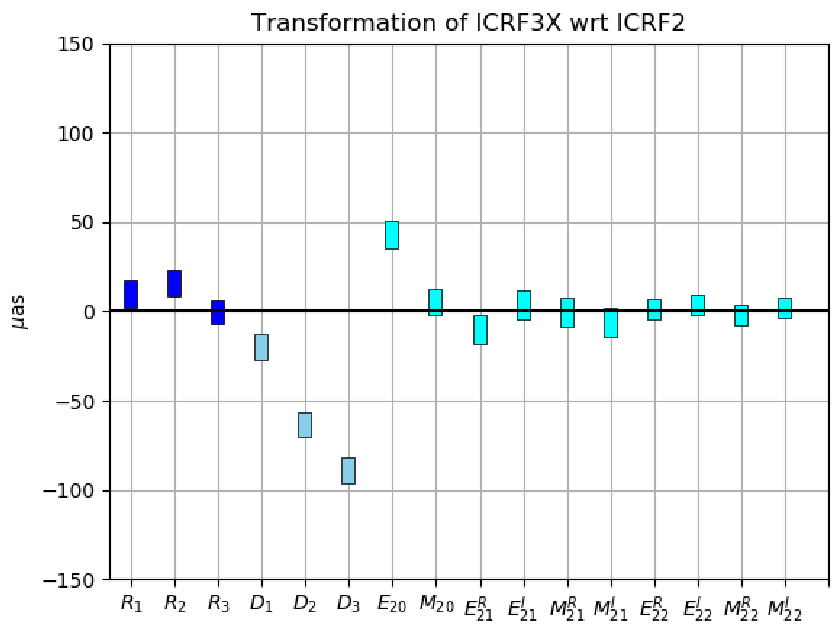
Model for comparing frames

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

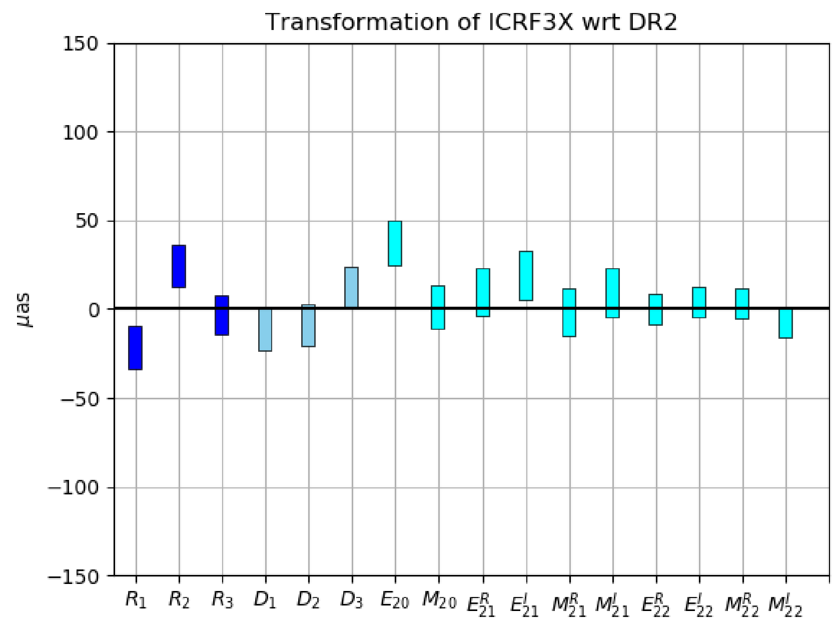
Mignard & Klioner (2012)

Deformations between frames

ICRF3-SX vs ICRF2



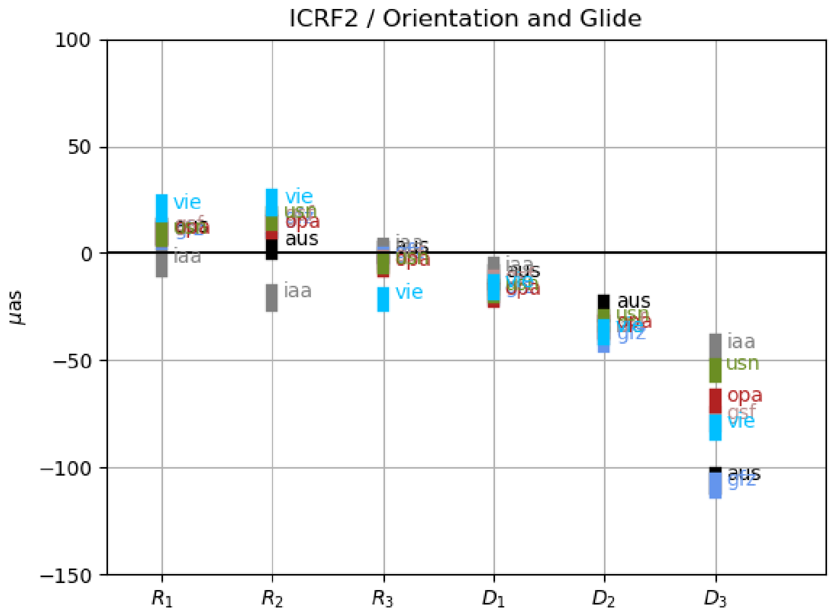
ICRF3-SX vs Gaia-CRF2

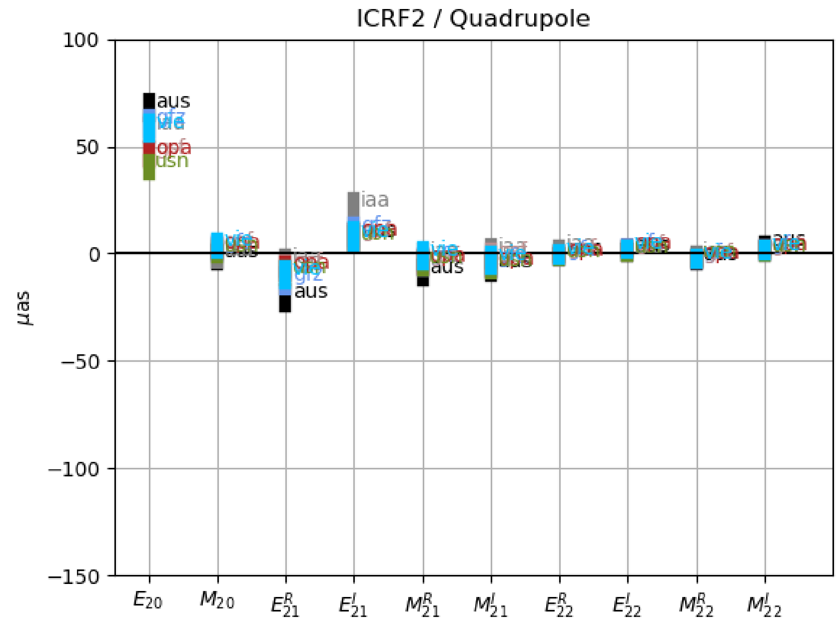


- Existence of significant glide parameters D2 and D3 and quadrupole term E20 between ICRF3-SX and ICRF2
- No significant deformations between ICRF3-SX and Gaia CRF2

Deformations ICRF3-SX vs ICRF2

Impact of VLBI software packages and analyst choices

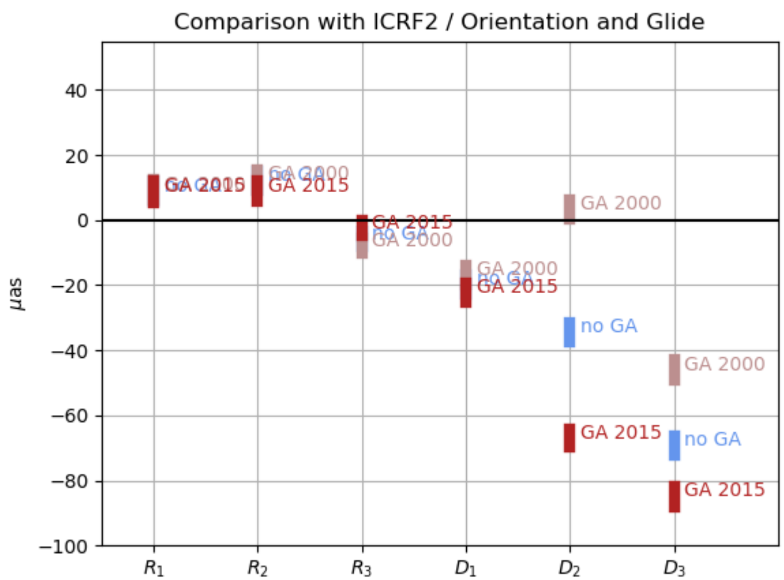


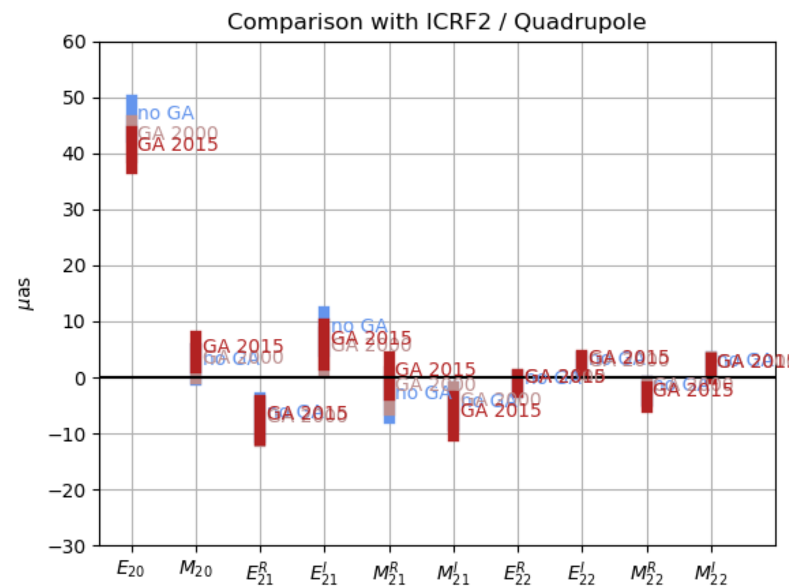


- Seven ICRF3-SX variants produced from different VLBI software packages or analysts
- All show similar deformations in D2, D3 and E20.

Deformations ICRF3-SX vs ICRF2

Impact of modeling Galactocentric acceleration

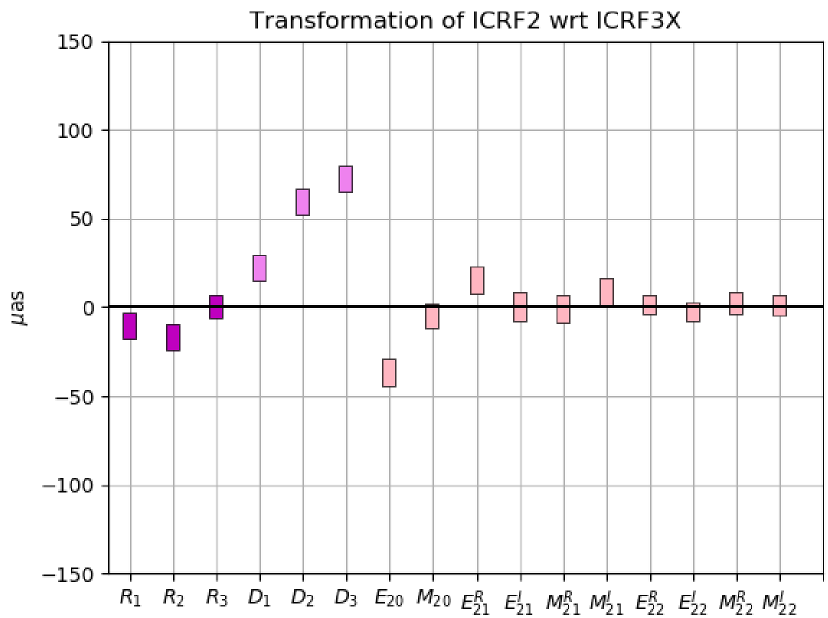




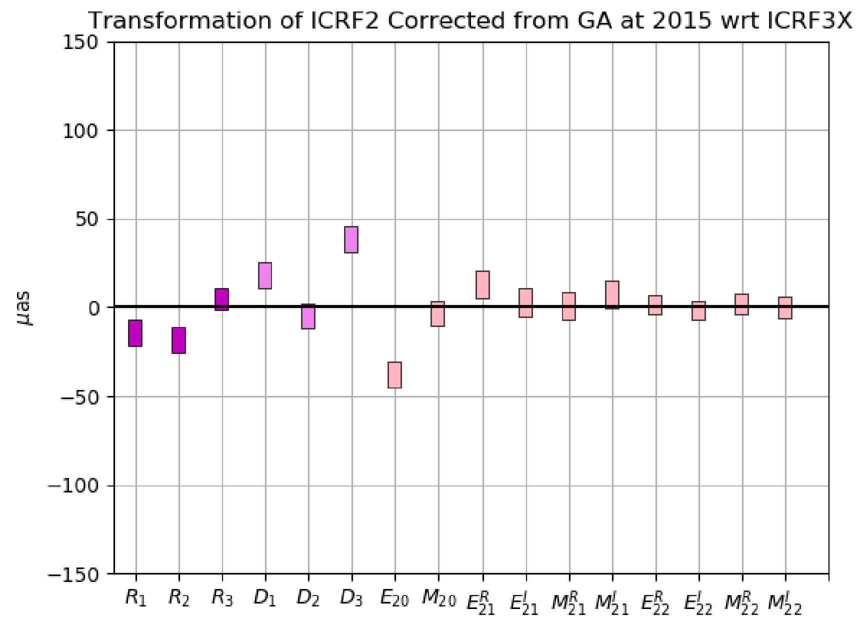
- Three ICRF3-SX variants produced by changing the catalog epoch (2000.0 or 2015.0) or not incorporating Galactocentric acceleration
- Incorporation of Galactocentric accelerration or changing the catalog epoch has a significant impact on the glide parameters D2 and D3.

Deformations ICRF3-SX vs ICRF2

ICRF3-SX vs ICRF2 (reproduced)



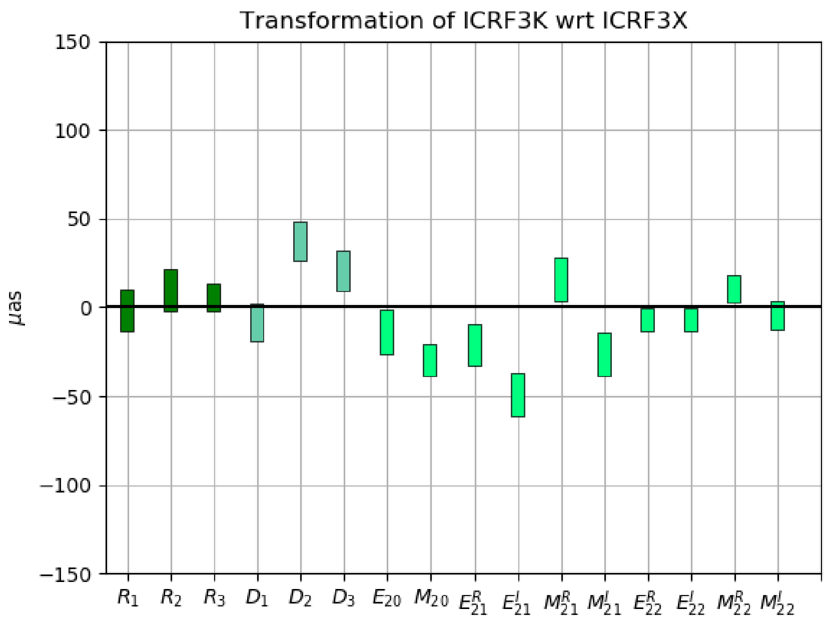
ICRF3-SX vs ICRF2 (reproduced with GA modeled at epoch 2015.0)



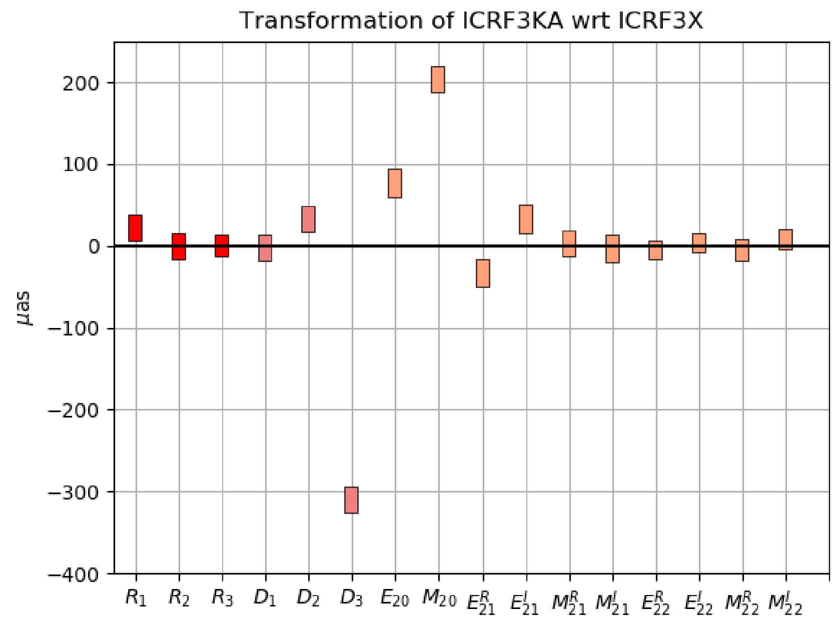
- Reproducing ICRF2 and modeling Galactocentric acceleration annihilates the D2 term and reduces the bias in D3 by 50%

Deformations: SX vs K and XKa

SX vs K



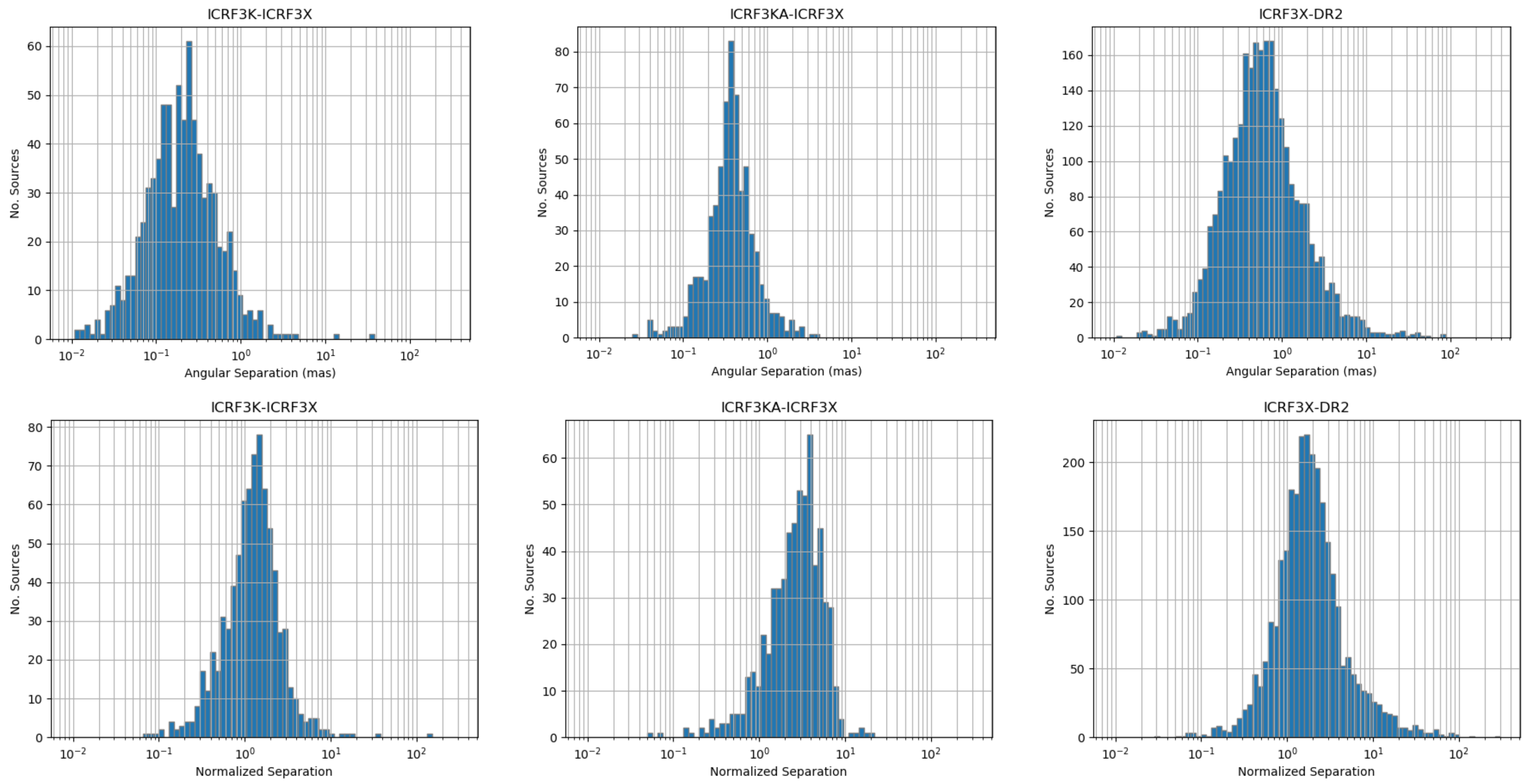
SX vs XKa



- No significant deformation between the SX band and K band frames
- Existence of significant deformation of the X/Ka frame (D3, E20, M20) originating from the limited (North-South) geometry of the network

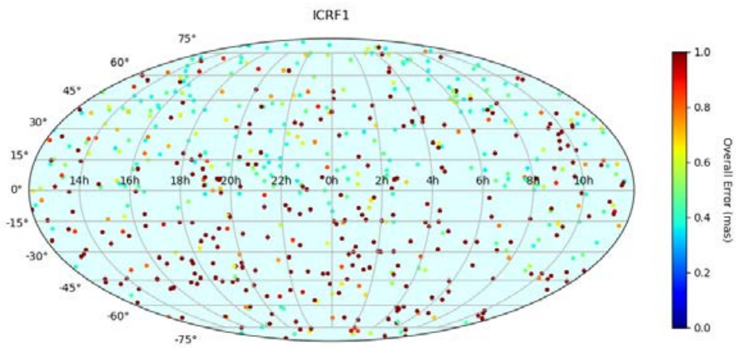
Consistency of multi-frequency positions

SX vs K | SX vs XKa | SX vs Gaia-CRF2



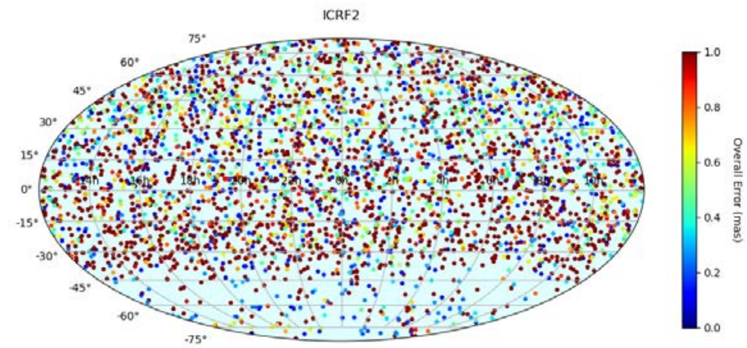
From ICRF1… to ICRF3

ICRF1 (1997)



608 sources

ICRF2 (2009)

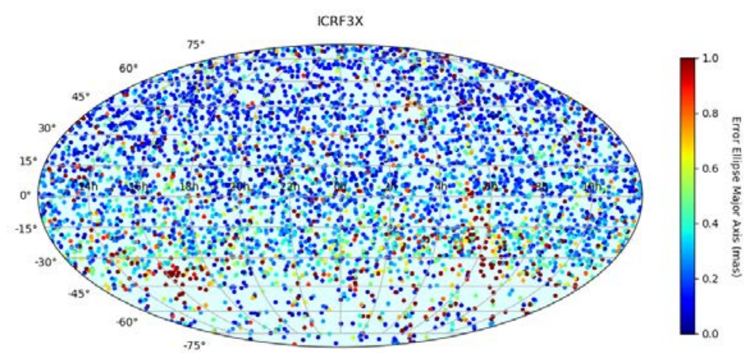


3414 sources

Main features of ICRF3

- Median position error decreased by a factor of 3.5 compared to ICRF2
- 4536 sources (35% more than in ICRF2)
- 3-frequency positions for 600 sources
- No deformations wrt Gaia-CRF2

ICRF3 (2018)



4536 sources

Release information

- ICRF3 endorsed by IVS and IERS
- ICRF3 released on 20 August 2018
- ICRF3 presented to IAU for adoption through resolution B2 (replacement of ICRF2 as of 1 January 2019)
- ICRF3 paper to be submitted in September

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August 29, 2018

The Third Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry

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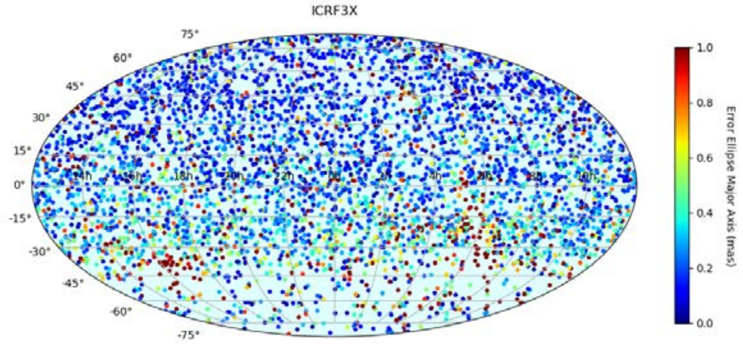
Thank you for your attention



Many thanks to the ICRF3 Working Group members for the team work accomplished during the past 6 years