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

<table>
<thead>
<tr>
<th>P. Charlot (Chair)</th>
<th>A. L. Fey</th>
<th>Z. Malkin</th>
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<tr>
<td>E. F. Arias</td>
<td>R. Gaume</td>
<td>A. Nothnagel</td>
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<td>D. Boboltz</td>
<td>D. Gordon</td>
<td>M. Seitz</td>
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<td>J. Boehm</td>
<td>R. Heinkelmann</td>
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<td>S. Bolotin</td>
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<td>G. Bourda</td>
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<td>A. de Witt</td>
<td>C. Ma</td>
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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 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)

- 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

74% of data

26% of data

Exclusive observations for ~2/3 of the sources

13.2 million observations
Data sets: K band (24 GHz)

Very Long Baseline Array (VLBA)

- 40 VLBA sessions (2002-2018)

Hartebeesthoek-Hobart observations

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

- 0.5 million observations
- 99% of data

- 1% of data
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)

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

<table>
<thead>
<tr>
<th>EOP</th>
<th>yp (µas)</th>
<th>yp (µas)</th>
<th>UT1 (µs)</th>
<th>X (µas)</th>
<th>Y (µas)</th>
</tr>
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<tbody>
<tr>
<td>Median error (ICRF3)</td>
<td>61</td>
<td>56</td>
<td>2.6</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td>wrms (ICRF3-IVS)</td>
<td>76</td>
<td>79</td>
<td>6.1</td>
<td>45</td>
<td>44</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>2.18</td>
<td>2.43</td>
<td>2.56</td>
<td>1.01</td>
<td>0.98</td>
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→ Very good consistency with the IVS series
ICRF3-SX

4536 sources

XXXth IAU General Assembly - Vienna - 27 August 2018
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
\[ \Delta \alpha \cos \delta = R_1 \cos \alpha \sin \delta - R_2 \sin \alpha \sin \delta + R_3 \cos \delta + D_1 \sin \alpha + D_2 \cos \alpha + a_{20}^M \sin 2\delta + (a_{21}^E \cos \alpha - a_{21}^M \sin \alpha) \sin \delta \]

\[ - (a_{21}^M \cos \alpha - a_{21}^M \sin \alpha) \cos 2\delta - 2 (a_{22}^E \cos 2\alpha + a_{22}^M \sin 2\alpha) \cos \delta - (a_{22}^M \cos 2\alpha - a_{22}^M \sin 2\alpha) \sin 2\delta, \]

\[ \Delta \delta = - R_1 \sin \alpha + R_2 \cos \alpha - D_1 \cos \alpha \sin \delta - D_2 \sin \alpha \sin \delta + D_3 \cos \delta + a_{20}^E \sin 2\delta - (a_{21}^E \cos \alpha - a_{21}^E \sin \alpha) \cos 2\delta - (a_{21}^M \cos \alpha + a_{21}^M \sin \alpha) \sin \delta - (a_{22}^E \cos 2\alpha - a_{22}^E \sin 2\alpha) \sin 2\delta + 2 (a_{22}^M \cos 2\alpha + a_{22}^M \sin 2\alpha) \cos \delta \]

Mignard & Klioner (2012)
Deformations between frames

ICRF3-SX vs ICRF2 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
Seven ICRF3-SX variants produced from different VLBI software packages or analysts

- All show similar deformations in D2, D3 and E20.
Three ICRF3-SX variants produced by changing the catalog epoch (2000.0 or 2015.0) or not incorporating Galactocentric acceleration.

Incorporation of Galactocentric acceleration 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)

- Reproducing ICRF2 and modeling Galactocentric acceleration annihilates the D2 term and reduces the bias in D3 by 50%
Deformations: SX vs K and 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
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 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

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