ICRF-3: Status, Plans, and Multi-wavelength Progress towards the next generation ICRF

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2015 May 17-21
Overview

• ICRF-2 history and benefits vs. ICRF-1

• Assessment of needed improvement in ICRF-3

• Plans for improving the ICRF
  more uniform precision: VCS-II
  more uniform spatial coverage: southern CRF
  improved frequency coverage: K, X/Ka

• Gaia: radio-optical frame tie
  Wavelength dependent systematic errors in CRFs
Overview of 2nd International Celestial Reference Frame

Brief description of how the current ICRF-2 was realized:

• S/X data (2.3/ 8.4 GHz or 13/ 3.6 cm) for **3414 sources**

• **6.5 Million group delay observations** 1979 to 2009

• No-Net-Rotation relative to ICRF-1

• Estimate TRF and EOPs internally from VLBI data
  Constrain to VTRF2008 (VLBI part of ITRF-08: *Böckmann et al, JGeod, 84, 2010*)
  as ITRF2008 was not yet released.
  4 constraints: Positions: No-Net-Translation, No-Net-Rotation
  Velocities: No-Net-Translation, No-Net-Rotation

• Produced from a single monolithic fit.
  Verified with solutions from various groups using independent software packages.

**Details in ICRF-2 Technical Note: Ma et al, IERS, 2009.**
http://adsabs.harvard.edu/abs/2009ITN....35....1M
**Geodetic impact by the switch from ICRF1-ext.2 to ICRF2**

ICRF1 Extension 2 – ICRF2

Improvements can be found for baselines including southern stations!
Geodetic impact by the switch from ICRF1-ext.2 to ICRF2

Table: EOP differences w.r.t. IGS

<table>
<thead>
<tr>
<th>EOP</th>
<th>ICRF1 Ext.2 fixed</th>
<th>ICRF2 fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WRMS</td>
<td>Chi2/dof</td>
</tr>
<tr>
<td>x-pole</td>
<td>123.4</td>
<td>3.3</td>
</tr>
<tr>
<td>y-pole</td>
<td>113.3</td>
<td>3.1</td>
</tr>
<tr>
<td>X-pole rate</td>
<td>318.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Y-pole rate</td>
<td>315.1</td>
<td>2.1</td>
</tr>
<tr>
<td>LOD</td>
<td>19.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Courtesy of D. MacMillan, GSFC

All EOPs improved with ICRF2!
Assessment of users for ICRF-3

Assessment of user relevant deficiencies

1. VLBA Calibrator Survey (VCS) is most (2/3) of ICRF-2 but positions are 5 times worse than the rest of ICRF-2

2. ICRF-2 is weak in the south especially below -40 deg Declination.

3. High frequency frames have more point-like sources but also fewer sources at present.
   As with S/X, high frequency CRFs are weak in the south.
• 3414 Sources in ICRF2. Huge improvement over ICRF1’s 608 sources
• ~2200 are single session survey sources (VLBA Calibrator Survey).
• Deficiency: ICRF-2 is sparse south of about -40 deg.
VLBA Calibrator Survey improvement

~3.7 times X improvement in precision

much more uniform distribution of the position uncertainties vs. declination.
VLBA Calibrator Survey improvement

VCS-I: ~1 mas precision
for 2200 sources

VCS-II:
RA 0.23 mas
Dec 0.39 mas
Improvement
~3.7 times

Credit: Gordon et al, GSFC, private communication, 2014
S/X-band Plan for Southern Improvements

- Recent southern work: Lovell’s talk
- 2013-15: Observe 100-200 strong (> 400 mJy) sources using the small, fast stations of the southern CRF Network at S/X-bands.

  Six (6) sessions completed.

- Goal > 100 scans per source, 50 µas precision

- **Weaker sources** observed with large telescopes: Parkes, DSS45, Hobart26, HartRAO
  100-200 sources over 2 years,

- Goal 20 scans/source, 100-150 µas precision
K-band (24 GHz) CRF: 275 sources

K-band full sky coverage collaboration: De Witt+ poster
First southern K-band fringes: Hobart-HartRAO (23 Aug 2013)
Data completing full sky coverage being processed.
VLBA approved time to densify the north -> expect 500+ sources total
K-band (24 GHz) CRF: > 500 sources

- K-band existing (Lany+, Charlot+).
- New K-band data from Bertarini et al collaboration (see De Witt+ poster)
  Data completing full sky from (Australia – South Africa) being processed.
  VLBA approved time to densify the north. Expecting > 500 sources total
X/Ka-band (8/32 GHz) CRF

- Median precision slightly better than ICRF-2. South cap adds 100 sources to ICRF-2
- 660 sources; Full sky coverage: NASA baselines CA to Madrid & Australia
  + recently added ESA Malargüe, Argentina to Tidbinbilla, Australia
Source Structure vs. Frequency (absolute scale)

The sources become better → smaller structure indexes (Fey & Charlot 1997)

Images credit: P. Charlot et al, AJ, 139, 2010
S/X zonal errors: ICRF2 vs. Recent S/X

GSFC-2014bp3 – ICRF2 Definings: 0.5 ppb zonal error in Declination

Credit: Gordon et al, GSFC, private .comm., 2014
ICRF-3 working group is exploring making the Defining sources to be a set of sources with common positions based on combined observations at

S/X (8 GHz)
K (24 GHz)
X/Ka (32 GHz)

and, perhaps, optical if possible.

Initial studies show some promise in the radio for this concept of a multi-wavelength ICRF.

Data is being taken and more studies will be done before a final decision is made.
Gaia-Optical vs. VLBI-radio:

Celestial Frame tie and
Accuracy Verification
Gaia: $10^9$ stars
• 500,000 quasars $V < 20$
  20,000 quasars $V < 18$
• radio loud 30-300+ mJy
  and optically bright: $V < 18$
  ~2000 quasars
• Accuracy
  100 $\mu$as @ $V = 18$
  25 $\mu$as @ $V = 16$

Gaia References:
Lindegren et al, IAU 248, 2008
http://adsabs.harvard.edu/abs/2008IAUS..248..217L

Mignard, IAU, JD-7, 2012
http://adsabs.harvard.edu/abs/2012IAUJD...7E..27M

• S/X Frame Tie Strategy:
  Bring new optically bright quasars
  into the S/X radio frame
  use sources with S/X fluxes 30-100 mJy
  (Bourda et al, EVN, Bordeaux, 2012)
Adding optically bright sources to radio

- S/X (3.6cm): Detected ~275 optically bright sources on long baselines
- Southern hemisphere additions just starting.
- XKa (9mm) will only see a fraction (10-20%) of these due to sensitivity limits
Optical vs. Radio systematics offsets

- Optical structure: The host galaxy may not be centered on the AGN or may be asymmetric. Review Zacharias & Zacharias (2014) who see evidence for many milli-arsecs of optical centroid offset. This could dominate the error budget.

- Optical systematics unknown, perhaps as large as 10 mas optical centroid offset? (Zacharias & Zacharias, AJ, 2014)
Summary of ICRF-3 goals:

• Improving VLBA Cal Survey’s 2000+ positions → 3X improvement: More uniform precision for all sources
• Improving southern observations → More uniform spatial coverage
• Improving number, accuracy, and southern coverage of high frequency frames 24, 32, 43? GHz (K, X/Ka, Q?) → Improved frequency coverage

• ICRF-3 completed by Aug 2018 in time for comparisons & alignment with Gaia optical frame
• Precision equal or better than Gaia (70 μas, 1-sigma)
• Improving set of optical-radio frame tie sources for Gaia