The Celestial Frame at X/Ka-band (8.4/32 GHz)

Christopher S. Jacobs
Jet Propulsion Laboratory, Caltech/NASA
J.E. Clark, C. Garcia-Miro, S. Horiuch, L.J. Skjerve, O.J. Sovers

30 March 2011
Overview

• Status of current radio-based celestial frames
  • ICRF2: wavelength 3.6cm, 3.4K objects, 40-100 µas
  • K-band: wavelength 1.2cm, 0.3K objects, 100-250 µas
  • X/Ka: wavelength 9mm, 0.5K objects, 200-300 µas

• Need southern stations: complementary geometry
  • Benefits southern cap, Declination accuracy

• Gaia/optical to VLBI/radio frame tie
  70-100 µas independent accuracy verification per source
  5-15 µas potential precision in 3-D frame tie
• ICRF2 Working Group (S/X-band, 3.6cm)
  C. Ma chair
  E.F. Arias, G. Bianco, D.A. Boboltz, S.L. Bolotin, P. Charlot, G. Engelhardt, A.L. Fey,
  R.A. Gaume, A.-M. Gontier, R. Heinkelmann, C.S. Jacobs, S. Kurdurov, S.B. Lambert,
  Z.M. Malkin, A. Nothnagel, L. Petrov, E. Skurikhina, J.R. Sokolova, J. Souchay, O.J. Sovers,
  V. Tesmer, O.A. Titov, G. Wang, V.E. Zharov, C. Barache, S. Bockmann, A. Collioud,

• KQ Collaboration (1.2cm, 7mm or 24, 43 GHz)
  G.E. Lanyi, P.I.
  D.A. Boboltz, P. Charlot, A.L. Fey, E. B. Fomalont, B.J. Geldzahler, D. Gordon,
  C.S. Jacobs, C. Ma, C.J. Naudet, J.D. Romney, O.J. Sovers, L.D. Zhang

• X/Ka-band Collaboration (9mm, 32 GHz)
  C.S. Jacobs, P.I.
Why observe in Radio? The ‘Window’

Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).

Visible light observable from Earth, with some atmospheric distortion.

Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio waves observable from Earth.

Long-wavelength radio waves blocked.

Water: 1.3 cm / 22 GHz

O₂ line: 0.5 cm / 60 GHz

W-band: 0.3 cm

Ka-band: 0.9 cm

X-band: 3.6 cm

S-band: 13 cm

L-band: 19-24 cm

Current Status of Celestial Reference Frames at radio wavelengths:

S/X ICRF2: 3.6cm, 8 GHz
K-band: 1.2cm, 24 GHz
X/Ka-band: 9mm, 32 GHz
ICRF2  S/X 3.6cm: 3414 sources

40 µas floor. ~1200 obj. well observed, ~2000 survey session only

Credit: Ma et al, eds. Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009
K-band 1.2cm: 278 Sources

VLBA all northern, poor below Dec. -30°. ΔDec vs. Dec tilt = 500 μas

X/Ka current results: 455 Sources

Cal. to Madrid, Cal. to Australia. Weakens southward. No $\Delta$Dec tilt

Credit: Jacobs et al, EVGA, Bonn, Germany, 2011
Accuracy of 404 X/Ka sources vs. S/X ICRF2 (current IAU standard)

RA: 213 μas = 1.0 nrad

Dec: 282 μas = 1.4 nrad

Credit: X/Ka: Jacobs et al, EVGA, Bonn, Germany, 2011
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009
Lack of direct Dual-band ion Calibrations and Lack of any Station in south Leads to poor ΔDec vs. Dec Zonal stability: 500 μas tilt

K(1.2cm) Declinations vs. S/X ICRF2 (current IAU standard)

Credit: K(1.2cm): Lanyi et al, AJ, 139,5, 2010
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009
9mm (X/Ka) vs. ICRF2 at 3.6cm (S/X)

Dual-band ion Calibrations and Station in south

Leads to better ΔDec vs. Dec

Zonal stability:

100+-100 μas tilt

X/Ka(9mm) Dec. vs. S/X ICRF2 (current IAU standard)

Credit: X/Ka(9mm): Jacobs et al, EVGA, Bonn, Germany, 2011
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009
Mean zonal error as shown by Δarc vs. arc ~20 μas (0.1 nrad)

When southern Station XYZ is fixed to S/X data estimate +-1cm.

Weaker constraint leads to 150 μas Zonal errors.
Improving X/Ka VLBI

Systems Analysis shows dominant Errors are

• Limited SNR/sensitivity
  – already increasing bit rates: 112 to 448 Mbps. Soon to 896?
• Instrumentation: already building better hardware
  – Ka-band phase calibrators, Digital Back Ends (filters)
• Troposphere: better calibrations being explored for turbulent variations in signal delay

• Weak geometry in Southern hemisphere
  – Limits accuracy to about 1 nrad (200 µas) level in Declination
  – No observations below Declination of -45 Deg!
  – DSN has only one southern site: Canberra, Australia (DSS 34)
  – Need 2nd site in the Southern hemisphere
Attacking the Error budget

DSN lack of Southern Geometry
Simulation of Added Southern Station

**Before Southern Data**

- 50 real X/Ka sessions augmented by simulated data
  - simulate 1000 group delays, SNR = 50
  - ~9000 km baseline: Australia to S. America or S. Africa

- Completes Declination coverage: cap region -45 to -90 deg
  - 200 µas (1 nrad) precision in south polar cap,
  - mid south 200-1000 µas, all with just a few days observing.

**After**

<table>
<thead>
<tr>
<th>Declination Sigma</th>
<th>Orange: &lt; 100 µas</th>
<th>Red: &lt; 200</th>
<th>Green: &lt; 300</th>
<th>Blue: &lt; 500</th>
<th>Purple: &lt; 1000</th>
<th>White: &gt; 1000</th>
</tr>
</thead>
</table>

30 Mar 2011 C.S. Jacobs
Gaia-Optical vs. VLBI-radio:

Celestial Frame tie and Accuracy Verification
Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids
  - radio: synchrotron from jet
  - optical: synchrotron from jet? non-thermal ionization from corona? big blue bump from accretion disk?

- Instrumental errors both radio & optical

- Analysis errors

Credit: Wehrle et al, μas Science, Socorro, 2009
Positions differences from ‘core shift’

- wavelength dependent shift in radio centroid.

- **3.6cm to 9mm core shift:**
  
  100 µas in phase delay centroid?

  <<100 µas in group delay centroid?  *(Porcas, AA, 505, 1, 2009)*

- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better
Source Structure vs. Wavelength

The sources become better

S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

K-band
24 GHz
1.2cm

Q-band
43 GHz
0.7cm

Ka-band
32 GHz
0.9cm

Image credit: P. Charlot et al, AJ, 139, 5, 2010
Gaia: $10^9$ stars

- 500,000 quasars $V < 20$
- 20,000 quasars $V < 18$
- radio loud 30-300+ mJy
- optically bright: $V < 18$
- ~2000 quasars

- Accuracy
  - 70 µas @ $V = 18$
  - 25 µas @ $V = 16$

Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7
Median optical magnitude $V_{\text{med}} = 18.6$ magnitude  
> 130 objects optically bright by Gaia standard ($V<18$)

[Image: 3D celestial map showing distribution of objects with different optical magnitudes.

Credit: Marscher

Optical brightness of X/Ka 9mm sources

30 Mar 2011, C.S. Jacobs
Gaia Optical vs. X/Ka 9mm frame tie

• 387 of 455 X/Ka 9mm objects with known optical $V$ magnitudes
  130 objects optically bright  ($V < 18$)
  206 objects optically weak   ($18 < V < 20$)
  51 objects optically undetectable ($V > 20$)
  68 objects no optical info yet ($V = ??$)

• Simulated Gaia measurement errors (sigma RA, Dec) for 336 objects: median sigmas $\sim 100 \mu$as per component

• VLBI 9mm radio sigmas $\sim 200 \mu$as per component and improving

• Covariance calculation of 3-D rotational tie using current 9mm radio sigmas and simulated Gaia sigmas
  $R_x \pm 16 \mu$as  <- Weak. Needs south polar VLBI ($Dec < -45$)
  $R_y \pm 13 \mu$as
  $R_z \pm 11 \mu$as

• Now limited by radio sigmas for which 2-3X improvement possible. Potential for rotation sigmas $\sim 5 \mu$as per frame tie component
Conclusions

• Astrometry using VLBI at 9mm (32 GHz)
  455 objects: RA, Dec accuracy 200, 280 µas

• Quasar astrophysics: 9mm position closer to optical position than S/X-based ICRF2, less extended structure expected

• Need southern complementary geometry for
  Full sky radio coverage, 70-100 µas accuracy at X/Ka 9mm

• Gaia tie:
  >130 objects radio loud @9mm and optically bright V<18
  Ties Gaia optical to VLBI radio frame
  Study astrophysics: core shift, jet vs. accretion disk
  Independent check on Gaia accuracy at 70-100 µas level
  5-15 µas potential precision for 3-D frame tie