The Celestial Reference Frame at Multiple Radio Wavelengths

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Overview

• How do sources change with wavelength?
• Overview of Celestial Frames
  S/X ICRF-2  >40 μas  3414 sources
  K-band  ~100 μas  268 sources
  Q-band  ~300 μas  131 sources
  X/Ka-band  ~220 μas  482 sources

• Future Prospects for Improvements:
  SNR: higher data rates 2-32 Gbps
  Instrumentation: Digital Back Ends, better clocks??
  Troposphere: Faster sweeps of sky, WVR cals
  Geometry: increase Southern hemisphere observations
  Optical frames: tieing to ESA’s Gaia mission c. 2021
Collaborators

• X/Ka-band Collaboration (9mm, 32 GHz)
  C.S. Jacobs, P.I.,
  J. Clark, C. García-Miró, S. Horiuchi, A. Romero-Wolf, I. Sotuela,
  L.G. Snedeker, O.J. Sovers

• 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

• 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. Böckmann,
• **Sensitivity worsens** at shorter wavelength/high frequency
  Higher system temperature: atmosphere H$_2$O (22 GHz), O$_2$ 60 GHz
  Antenna pointing more difficult
  Antenna surface shape control more difficult
  Atmospheric absorption
  Resolved sources

• **Quasar astrophysics gets better**
  Sources more compact at shorter wavelength (higher frequency)
  More sources resolved at higher frequency-> less sources
  Less extended structure: plume is steep spectrum
  Core shift reduced at short wavelength/high frequency
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

Active Galactic Nuclei (*Marscher*)

Features of AGN: *Note the Logarithmic length scale.*

- Frequency dependent Core shift: 8 GHz -> 32 GHz (3.6cm->9mm)
  - ~100 µas in phase delay (e.g. Sokolovsky *et al*, 2011; Kovalev *et al*, 2008)

- Higher frequencies closer to blackhole origin. And perhaps closer to optical position.
Source Structure vs. Wavelength

S-band
2.3 GHz
13.6 cm

X-band
8.6 GHz
3.6 cm

K-band
24 GHz
1.2 cm

Q-band
43 GHz
0.7 cm

Ka-band
32 GHz
0.9 cm

The sources become better ---->

Images credit: P. Charlot et al, AJ, 139, 5, 2010
Celestial Reference Frames

Current Status of CRF at radio wavelengths:

S/X ICRF2: 3.6cm, 8 GHz (Ma et al, IERS, 2009)

(Charlot et al, AJ, 2010)

X/Ka-band: 9mm, 32 GHz (García-Miró et al, IVS, 2012)
ICRF2  S/X: 8.4 GHz, 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 24GHz, 1.2cm: 278 Sources

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

X/Ka 32GHz, 9mm Dec results: 469 Sources

Cal. to Madrid, Cal. to Australia. Weakens southward. No ΔDec tilt

Credit: García-Miró et al, IVS, Madrid Spain, 2012
X/Ka current RA results: 469 Sources

Credit: García-Miró et al, IVS, Madrid Spain, 2012

Cal. to Madrid, Cal. to Australia. Weakens south of Dec = -15deg
X/Ka (9mm) vs. ICRF2 at S/X (3.6cm)

Accuracy of 450 X/Ka sources vs. S/X ICRF2 (current IAU standard)

RA: 194 µas = 0.9 nano-rad

Dec: 270 µas = 1.3 nano-rad

Attacking the Error budget

• **SNR**: low cost disk drives -> more bits!

• **Instrumentation**:
  - IVS: Ruszczyk et al, 2012; Tuccari, 2012
  - DBE: Digital Baseband Conversion, Filters García-Miró et al, 2012
  - Phase calibration for X/Ka-band Hamell, Tucker, Calhoun, 2003

• **Troposphere cals**:
  - Faster coverage of sky: VLBI-2010

• **Southern Geometry**
  - S/X: HARTRAO. Auscope+: Hobart, Katherine, Yaragadee, Warwick
  - K: HARTRAO, S. Africa? Tidbinbilla, Australia?
  - Q: ??
  - X/Ka: Malargue, Argentina, Hobart? New Norcia?
Attacking the Error budget: SNR

• Current data

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>S/X RDVs</td>
<td>256 Mbps</td>
</tr>
<tr>
<td>K/Q</td>
<td>128 Mbps</td>
</tr>
<tr>
<td>X/Ka</td>
<td>448 Mbps</td>
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- (program dormant at present)

• Mark-5C

- 2048 Mbps (within next year or so?)
  -> 4 to 16X in data rate
  -> 2 to 4 in sensitivity, delay precision
- 4096 Mbps (later)

• Mark-6

  (Whitney, Capallo, Lapsley, IVS, 2012)

- 16 Gbps sustained
# Summary of Instrumental Improvements

<table>
<thead>
<tr>
<th>Instrument</th>
<th>MkIV</th>
<th>DBE/Mk5-C</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Filters</td>
<td>Analog 7-pole Butterworth</td>
<td>Digital FIR phase linear</td>
<td>removes phase ripple, chans identical</td>
</tr>
<tr>
<td>Spanned bandwidth</td>
<td>360 MHz</td>
<td>500-1000 MHz</td>
<td>Mk4 limit</td>
</tr>
<tr>
<td>Mk4 rate @ start</td>
<td>112 Mbps</td>
<td>SNR limited trop/inst. limited</td>
<td></td>
</tr>
<tr>
<td>@ max.</td>
<td>896 Mbps</td>
<td>trop/inst. limited</td>
<td></td>
</tr>
<tr>
<td>Mk5 rate @ start</td>
<td>2048 Mbps</td>
<td>trop/inst. limited</td>
<td></td>
</tr>
<tr>
<td>@ max.</td>
<td>4096 Mbps</td>
<td>6X sensitivity</td>
<td></td>
</tr>
<tr>
<td>Phase Cal:</td>
<td>S/X, K, Q</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>X/Ka</td>
<td>No</td>
<td>Yes</td>
<td>removes 100s of psec</td>
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Calibrating Troposphere Turbulence

- Monitor 22 GHz/1.3cm water (rotational) line brightness temperature along line-of-sight

- JPL Advanced Water Vapor Radiometer
  - ~ 1 deg beam better matches VLBI
  - improved gain stability
  - improved conversion of brightness temperature to path delay (Tanner & Riley, R.Sci, 2003)

- Demonstrated ~20 µas calibration accuracy
  Goldstone-Madrid 8000 km baseline using X/Ka phase delays
  *Jacobs et al, AAS Winter 2005.*
  *Bar Sever et al, IEEE, 2007.*

- A-WVRs deployed at Goldstone/Madrid
  Seeking funding for Tidbinbilla, Aus
  not used yet for Operations

- VLBI-2010: Fast slewing (~5 deg/sec) to allow better estimation from covering full geometry before troposphere can change
Southern Hemisphere Stations for CRF

- **26-m S/X now**, K-band now, but little used
- **34-m S/X**, 70-m K-band, 34-m X/Ka
- **12-m S/X**, 2-14 GHz? S/X/Ka???
- **34-m X/Ka** operational Fall 2012
Potential Southern VLBI Stations?

- **X/Ka: ESA Deep Space Antenna DSA-03**
  - **Malargue, Argentina:**
    - Fall-2012 NASA/ESA collaboration
    - 35-m, X/Ka-band, 9,500 km baseline
    - Dry desert site is good for Ka-band

- **K-band: Hart, South Africa**
  - 26-m, surface good to K-band
  - Was broken ~2yr, Now repaired
  - Resurfaced in 2005 (0.5mm RMS) efficient to 22 GHz

- **S/X: Auscope, Warwick, NZ; HARTRAO, S. Africa**
Simulation: 9000km all-Southern baseline

- 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.

**Declination Sigma**
- Orange: < 100 µas
- Red: < 200
- Green: < 300
- Blue: < 500
- Purple: < 1000
- White: > 1000
Gaia: $10^9$ stars
- 500,000 quasars $V< 20$ mag
  - 20,000 quasars $V< 18$ mag
- radio loud 30-300+ mJy
  and optically bright: $V<18$ mag
  - ~2000 quasars
  (Mignard, next talk: 4.03)

- X/Ka:
  - 130 sources optically bright ($V>18$)
  Frame tie simulated precision ~ 10 µas
  Improving with more data arriving.
  (García-Miró et al, IVS, 2012)

- S/X: Strategy: Bring new quasars which are optically bright into the radio frame
  (Charlot & Bourda, this session: 4.10)

- Quasar Precision
  - 70 µas @ $V=18$
  - 25 µas @ $V=16$

(V magnitudes: Veron-Cetty & Veron, 2010)
Conclusions

• Increasing frequency -&gt; **lower sensitivity**, but more compact

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  - Instrumentation: Digital Back Ends, better clocks?
  - Troposphere: faster sweeps of sky, WVR calibrations
  - Improving Southern geometry: Auscope+, HART, Malargue

• **Frame tie** ~2021 VLBI/Gaia optical tie precision ~10 μas.