The X/Ka-band Extragalactic Reference Frame

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Overview

- Ka-band pros and cons

- 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
Ka-band on Edge of Radio Window

- O₂ line: 0.5 cm/60 GHz
- H₂O line: 22 GHz
- W-band: 0.3 cm
- L-band: 19-24 cm
- GPS
- Ka-band: 0.9 cm
- X-band: 3.6 cm
- S-band: 13 cm
Motivation for Ka-band: 9mm/32 GHz

- Astrometry, Geodesy and Deep Space navigation, have been at 3.6cm/8.4 GHz (X-band) with 2.3 GHz (S-band) plasma cals

Ka-band (9mm/32 GHz) Advantages
- More compact sources which should lead to more stable positions!
- Higher Telemetry Rates: +5 to +8 dB
- Smaller, lighter RF spacecraft systems
- Avoid S-band RFI issues
- Ionosphere & solar plasma down 15X!! at 32 GHz (Ka-band) compared to 8 GHz thus observe closer to Sun & Galactic center

Disadvantages of Higher radio frequencies:
- More weather sensitive, higher system temp.
- Shorter coherence times
- Weaker sources, Many sources resolved
- Antenna Pointing more difficult

Mars Reconnaissance Orbiter 2005 demonstrated Ka-band Communications and Navigation.
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°. \( \Delta \text{Dec vs. Dec tilt= 500 \, \mu as} \)

X/Ka current Dec results: 469 Sources

Cal. to Madrid, Cal. to Australia. Weakens southward. No ΔDec tilt
X/Ka current RA results: 469 Sources

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

S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, IERS, Germany, 2009
Improving VLBI

Systems Analysis shows dominant Errors are

- Limited SNR/sensitivity
  - already increased bit rates: 112 to 448 Mbps. Soon to 2048?
- Instrumentation: already building better hardware
  - Ka-band phase calibrators, Digital Back Ends (filters)
- Troposphere: better calibrations being explored

- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 1 nrad (200 μas) level
  - No observations below Declination of -45 Deg!
  - DSN at X/Ka has only Canberra, Australia (DSS 34)
  - Need 2nd site in the Southern hemisphere especially for upcoming southern ecliptic missions
How do we improve accuracy?
Southern Coverage!

Figure credit: www.spacetoday.org/images/SolSys/DeepSpaceNetwork/NASA_DSN_WorldMap.gif
Simulation of Added Southern Station

50 sessions, No Sim. 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.

- Horiuchi et al talk will show plan to attack this area.

Adding Simulated data

Declination Sigma
- Orange: < 100 μas
- Red: < 200
- Green: < 300
- Blue: < 500
- Purple: < 1000
- White: > 1000
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: $V < 18$
- $\approx 2000$ quasars

- Accuracy
  - $70 \, \mu$as @ $V = 18$
  - $25 \, \mu$as @ $V = 16$

Figure credit: [http://www.esa.int/esaSC/120377_index_l_m.html#subhead7](http://www.esa.int/esaSC/120377_index_l_m.html#subhead7)
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
- Majid et al talk will give complementary info on source physics
Median optical magnitude $V_{\text{med}} = 18.6$ magnitude  \((71 \text{ obj. no data})\)  

> 130 objects optically bright by Gaia standard ($V<18$)
Gaia Optical vs. X/Ka 9mm frame tie

• 398 of 469 X/Ka 9mm objects with known optical V magnitudes
  132 objects optically bright (V < 18)
  213 objects optically weak (18 < V < 20)
  53 objects optically undetectable (V > 20)
  71 objects no optical info yet (V = ??)

• Simulated Gaia measurement errors (sigma RA, Dec) for 345 objects: median sigmas ~ 100 μas per component

• VLBI 9mm radio sigmas ~200 μas per component and improving

• Covariance calculation of 3-D rotational tie using current 9mm radio sigmas and simulated Gaia sigmas
  Rx +- 14 μas <- Weak. Needs south polar VLBI (Dec < -45)
  Ry +- 11 μas
  Rz +- 10 μas

• Now limited by radio sigmas for which 2-3X improvement possible. Potential for rotation sigmas ~5 μas per frame tie component
Conclusions

- Future tracking is moving to Ka-band: +5 to 8dB telemetry
- Quasar astrophysics: Ka position closer to optical position than S/X-based ICRF2, less extended structure expected
- Ka-band Celestial Frame: 469 Active Galactic Nuclei
- However, DSN lacks 2nd southern station
- Simulated Southern Geometry shows great promise
- 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