The Celestial Reference Frame at X/Ka-band: Status & Prospects for Improving the South

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9-12 October 2012
Overview

• How do sources change with wavelength? Why Ka-band?

• X/Ka in the context of other Celestial Frames
  S/X ICRF-2  >40 \( \mu \text{as} \)  3414 sources
  K-band  \(~100 \mu \text{as}\)  268 sources
  Q-band  \(~300 \mu \text{as}\)  131 sources
  X/Ka-band  \(~220 \mu \text{as}\)  482 sources

• Prospects for Improvements:
  SNR, Instrumentation, Troposphere

• Improving Southern Geometry:
  ESA-DSN collaboration for X/Ka: Malargue, Argentina

• Optical frames: tying to ESA’s Gaia mission c. 2021
• **Sensitivity** _worsens_ at shorter wavelength/high frequency
  Higher system temperature: atmosphere $\text{H}_2\text{O}$ (22 GHz), $\text{O}_2$ 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’

- **O₂ line**: 0.5 cm/ 60 GHz
- **Water**: 1.3 cm/ 22 GHz
- **L-band**: 19-24 cm
- **W-band**: 0.3 cm
- **Ka-band**: 0.9 cm
- **X-band**: 3.6 cm
- **S-band**: 13 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

The sources become better ----->

Ka-band
32 GHz
0.9 cm

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)

**K-band:** 1.2cm, 24 GHz  
(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

Cal. to Madrid, Cal. to Australia. **Weakens southward. No $\Delta$Dec tilt**
X/Ka current RA results: 469 Sources

Cal. to Madrid, Cal. to Australia. Weakens south of Dec = -15deg

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

• **Southern Geometry**  
  - S/X: HARTRAO. Auscope+: Hobart, Katherine, Yaragadee, Warwick  
  - K: HARTRAO, S. Africa? Tidbinbilla, Australia?  
  - Q: ??  
  - X/Ka: Malargue, Argentina, Hobart? New Norcia?
Simulation: 9000km all-Southern baseline

50 sessions, No Sim. Southern Data       Adding Simulated 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
  144 south polar candidate sources (Sotuela et al, Porto, 2011)
  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
ESA’s Argentina 35-meter antenna **adds 3 baselines** to DSN’s 2 baselines
- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina
Malargue: The Next X/Ka VLBI Station

X/Ka: ESA Deep Space Antenna DSA 03

- **Malargue, Argentina**
- Fall-2012 NASA/ESA collaboration
- 35-m, X/Ka-band, 9,500 km baseline
  - Argentina-Australia covers south polar cap
  - Full sky coverage for X/Ka!!
- Argentina-California & Australia-California orthogonal baselines for mid-latitudes
- Dry desert site is good for Ka-band
- HA-Dec coverage: Tidbinbilla to Malargue:

![Antenna Image]

Malargue, Argentina 35-meter as of 26 Sept. 2012

ESA Deep Space Antenna
*X/Ka-band capable*
Validate Collaboration: Cebreros, Spain

• ESA sites first reference frame VLBI fringes
  Needed compatible VLBI recorder:
    Portable: laptop, USB 3.0 drives
    custom signal processing: 16 chan, 4 MHz, 2-bit, 256 Mbps
  Designed and validate pointing interfaces
  Validated instrumental stability
  Tied together ESA-NASA terrestrial frames

• Malargue Deep Space Antenna 03 to be ready in fall 2012
  Cebreros, Spain however was operational & close to DSN Robledo site

• Validation tests in July 2012
  Fringes X and Ka from ESA Cebreros DSA 02 to DSN Robledo DSS 55
  Initial Terrestrial frame tie to +- 2 cm
  Stability tested via 2000 sec phase delay on strong source
  Allan Standard deviation shows instrumentation stable
  to better than troposphere noise!
Ka-band Fringes! 16 chan x 4MHz x 2-bit=256 Mbps

ESA sites had never done reference frame VLBI
Needed compatible VLBI recorder

Time (sec) since 201:00:50:01
RMS ~2mm/6psec  (yscale: 360 deg = 9mm = ~30 psec)
Interferometer Stability: Allan St. Dev.

- Cebreros-DSS 55
  Ka-band, 10km baseline, 2000 sec

- Allan Deviation: 1 - 1000 sec
- Slope = -0.69
  consistent with 2-D Kolmogorov frozen flow trop noise (-2/3)
  (Treuhaft & Lanyi, Rsci,1987)

- Slope 1-20 sec shows some sign of white noise limitation
  (slope ~ -1)

- Slope plateaus around 25-75 sec
  3-D trop turbulence noise from small scale fluctuations?

Validates ESA-DSN baseline and interfaces. Malargue next. . .
ESA’s Argentina 35-meter antenna adds 3 baselines to DSN’s 2 baselines
- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina
Gaia/VLBI frame tie and accuracy verification

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, this meeting)

- X/Ka:
  - 130 sources optically bright ($V > 18$)
  - Frame tie simulated precision ~ 10 $\mu$as per rotation angle (1-sigma).
  - 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 meeting)

- Quasar Precision
  - 70 $\mu$as @ $V = 18$
  - 25 $\mu$as @ $V = 16$

(Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7)

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

• Increasing frequency -> lower sensitivity, but more compact

• Celestial Frame Overview:
  
  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 (2Gbps), Instrumentation: DBEs, PCGs, Trop.: WVRs

• ESA-DSN collaboration: add Malargue, Argentina
  Improve from 2 to 5 baselines, orthogonal mid-lat baselines
  Full sky coverage by accessing south polar cap!

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

• Current data

  S/X RDVs  256 Mbps
  K/Q      128 Mbps (program dormant at present)
  X/Ka     448 Mbps

• 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>
</tr>
</thead>
<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>2048 Mbps</td>
<td>SNR limited trop/inst. limited</td>
</tr>
<tr>
<td>@ max.</td>
<td>896 Mbps</td>
<td>4096 Mbps</td>
<td>trop/inst. limited</td>
</tr>
<tr>
<td>Mk5 rate @ start</td>
<td></td>
<td>2048 Mbps</td>
<td>6X sensitivity</td>
</tr>
<tr>
<td>@ max.</td>
<td></td>
<td>4096 Mbps</td>
<td></td>
</tr>
<tr>
<td>Phase Cal: S/X, K, Q</td>
<td>Yes</td>
<td>Yes</td>
<td>removes 100s of psec</td>
</tr>
<tr>
<td>X/Ka</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
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
The Potential for a Ka-band Worldwide VLBI Network

C. S. Jacobs¹,

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9 Oct 2012 C.S. Jacobs
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. Kubby, D. 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,
Attacking the Error budget

- SNR can be improved +8 dB!
- Instrumentation:
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering
- Troposphere cals: WVR

- Southern Geometry
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 \( \sim 100 \mu as \) 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
  \( R_x \) +/− 14 \( \mu as \) \( \text{<- Weak. Needs south polar VLBI (Dec < -45)} \)
  \( R_y \) +/− 11 \( \mu as \)
  \( R_z \) +/− 10 \( \mu as \)
- Now limited by radio sigmas for which 2-3X improvement possible.
  Potential for rotation sigmas \( \sim 5 \mu as \) per frame tie component
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
Attacking the Error budget

• SNR can be improved +8 dB!

• **Instrumentation:**
  
  Phase calibration with test signals
  
  Digital Baseband Conversion & Filtering

• Troposphere cals: WVR

• Southern Geometry
Attacking the Error budget

- SNR can be improved +8 dB!
- Instrumentation:
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering
- Troposphere cals: WVR
- Southern Geometry
### History of Astrometry: Star positions

<table>
<thead>
<tr>
<th>Year</th>
<th>Method</th>
<th>Technique</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 B.C.</td>
<td>Hipparchus</td>
<td>Precession</td>
<td>50 asec/yr</td>
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<tr>
<td>Telescope era:</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1718 A.D.</td>
<td>Halley</td>
<td>proper motions</td>
<td>1 asec/yr</td>
</tr>
<tr>
<td>1727</td>
<td>Bradley</td>
<td>annual aberration</td>
<td>20 asec</td>
</tr>
<tr>
<td>1748</td>
<td>Bradley</td>
<td>18.6 yr nutation</td>
<td>9 asec</td>
</tr>
<tr>
<td>1838</td>
<td>Bessel</td>
<td>parallax</td>
<td>~ asec</td>
</tr>
<tr>
<td>1930/40s</td>
<td>Jansky, Reber</td>
<td>Radio astronomy</td>
<td></td>
</tr>
<tr>
<td>1960s</td>
<td>Several groups</td>
<td>Very Long Baseline Interferometry (VLBI) invented</td>
<td></td>
</tr>
<tr>
<td>1970s</td>
<td>“</td>
<td>VLBI</td>
<td>sub-asec</td>
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<tr>
<td>1980s</td>
<td>“</td>
<td>“</td>
<td>few 0.001 asec</td>
</tr>
<tr>
<td>1990s</td>
<td>“</td>
<td>“</td>
<td>&lt; 0.001 asec</td>
</tr>
<tr>
<td>2000s</td>
<td>“</td>
<td>“</td>
<td>~0.0001 asec</td>
</tr>
<tr>
<td>2010s</td>
<td>Gaia</td>
<td>Optical astrometry</td>
<td>25-70 μas for V=16-18 quasar</td>
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<tr>
<td>2010s</td>
<td>ESA-DSN? X/Ka 9mm VLBI</td>
<td></td>
<td>70 μas 0.3 Jansky quasar</td>
</tr>
</tbody>
</table>
• VLBA ten 25m antennas
  12 sessions each 24 hours
  120K delay/rate obs. pairs
  ~65-180 sources /session
  3-5 snapshots, 2 min each
  400 MHz spanned band
  128 Mbps record rate

• Simultaneous astrometry and imaging

Troposphere Solution 1: Better Estimation

- Modified Least Squares to account for observation correlations -- both temporal and spatial.


- Model increases information available to the estimation process:
  1) Reduces parameter biases
  2) Reduces parameter sigmas

- Validation: Currently improves agreement $X/Ka$ vs. $S/X$ catalogs by about 10% in Declinations.
  Expect ~30% after SNR & phase cal errors peeled away to reveal troposphere errors.
Ka-band candidates: 498 sources identified

Right Ascension (hours)

Ka candidate criteria: 200 mJy, 70% flux in unresolved X-band core
South polar cap is well covered, ready for observations.
“First Light”: 1st Ka-band Fringes outside DSN!

Amplitude Corrected_Lag/Delay_Data 11se223 S5/S12 OT 081

Effelsberg 100-meter to DSS 55 34-meter BWG
DOY 223, source OT 081, 28 x 4MHz chan @2-bit, 448 Mbps

100-m photo credit: N. Tacken, Max Planck Inst. for Radio Astronomy
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) provides
- 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

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

Picture credit: SOHO/ESA/NASA
Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids
  - radio: synchrotron from jet
    frequency dependent structure
    frequency dependent core shift

- optical: synchrotron in jet?
  non-thermal ionization in corona?
  big blue bump?

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 $\Delta$Dec vs. Dec

 Zonal stability: $100 \pm 100 \mu$as tilt

X/Ka(9mm) 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
9mm (X/Ka) vs. ICRF2 at 3.6cm (S/X)

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.

X/Ka(9mm) 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
How Does VLBI Work?

The Observing Platform
“Budget” of Effects contributing to Interpretation of Results

<table>
<thead>
<tr>
<th>Term</th>
<th>Size</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td>Geometry</td>
<td>6,000,000,000 mm</td>
<td>... mm</td>
</tr>
<tr>
<td>Orbital aberration</td>
<td>600,000</td>
<td>1</td>
</tr>
<tr>
<td>General Relativity</td>
<td>2,000</td>
<td>2</td>
</tr>
<tr>
<td>Tectonic motion</td>
<td>2,000</td>
<td>2</td>
</tr>
<tr>
<td>Tidal motion</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>Non-tidal motion</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Earth rotation/pole motion</td>
<td>20,000</td>
<td>2</td>
</tr>
<tr>
<td>Nutation/precession</td>
<td>300,000</td>
<td>3</td>
</tr>
<tr>
<td>Extended sources</td>
<td>50</td>
<td>3</td>
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<tr>
<td>Antenna structure</td>
<td>10,000</td>
<td>10</td>
</tr>
<tr>
<td>Electronics</td>
<td>300,000</td>
<td>5</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>Troposphere</td>
<td>20,000</td>
<td>20</td>
</tr>
</tbody>
</table>
Polar Motion Spiral

Polar Motion vs. Time

Effect ~ 10 m

Calibrated to ~1cm with
GPS + VLBI + …

Length Of Day Spectrum, UT1 vs. TAI


Length Of Day Spectrum

and

UT1 -- TAI
Nutation: The Earth’s axis is like a Top

1980 IAU Model vs. VLBI observed
Nutation

Credit: www.4physics.com

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Accuracy has been limited by SNR

Solution:

1) More bits:
   4X operational
   8X R&D
   in ~6 months
   yields +5 dB SNR

   16X in 2-3 years
   32X in 3-5 years

2) Ka pointing

   Now with improved
   Pointing calibrations
   ~3 dB more SNR

   Total vs. early passes
   +8 dB SNR increase!

Data scatter has been SNR limited for SNR < 15 dB
Higher data rate hardware being developed

IF select switch:
12 inputs allows multiple bands, multiple antennas

Command & Control

Sampler: 1280 MHz, 8-bit/sample

Mark-5C recorder

Copper to fiber, Digital filter, Format

Design: Navarro et al., IVS, 2010. Photo credit: Les White
Need instrumental Phase calibrations

Problem:
180 psec ~diurnal effect

Solution:
Ka-band Phasecal Prototype Demo’d → Units being Built. Operations in ~1 year

Proto-type shows need for calibrations. Credit: C. Jacobs, B. Tucker, L. Skjerve

9 Oct 2012, C.S. Jacobs
Example: Ka-band Antenna Pointing

White pts. Represent Non-detection

Note Northern concentration of non-detects

Later, we got independent confirmation from ACME automated bore sight system of 18 mdeg errors

Credit: M. Vasquez, G. Baines, D. Rochblatt, C. Jacobs, C. Snedeker
How Does VLBI Work?

The Concept:
Point Source at Infinity
Point Source at Infinity as Reference Beacon

How does VLBI work?

• Point source at infinity as a direction reference
  Extragalactic “nebulae” idea from
  Laplace (1749-1827) and
  Wm. Herschel (1738-1822): in 1785
  realized that “nebulae” likely very distant

• Advantage: sources don’t move

BUT at a distance of a billion light years . . .

• The price to be paid is
  Very weak sources 1 Jy = 1.0E-26 watt/m**2/Hz
  need lots of square meters => 34 - 70m Antenna
  lots of Hz bandwidth => 0.1 to 4 Gbps
  low system temperature => Tsys = 20 - 40 Kelvin
AGN Centaurus-A in X-ray, Optical, Radio

Active Galactic Nuclei (AGN) schematic

Schematic of
Active Galactic Nuclei
Redshift $z \sim 0.1$ to 5
Distance:
billions light years
$Parallax = 0$
$Proper motion$
$< 0.1 \text{ nrad/yr}$

Centroid of radiation
Gets closer to central engine (black hole)
As one goes to higher frequencies, therefore,

$Ka$-band (9mm, 32 GHz)
is better than
$X$-band (3.6cm, 8.4 GHz)

http://heasarc.gsfc.nasa.gov/docs/objects/agn/agn_model.html

Paradigm of “Sailing by the stars”

Photo Credit: Dimitry Bobroff, www.ludmillaalexander.com

Credit for sextant/octant: en.wikipedia.org/wiki/Sextant (GNU Free Doc license)
Navigation & Astrometry: Historical Perspective

Photo credit: Tom Grill Images, tomgrill.com (www.arsmachina.com/images/compass7012-1.jpg)
Simulated Coverage:
Dec +10 deg to −90 deg