Tying multiple Radio Wavelength Celestial Frames to the Gaia Optical Frame

Christopher S. Jacobs, Jet Propulsion Laboratory, California Institute of Technology
Overview: Optical vs. Radio Celestial Frames

- **History:** VLBI at SX (8 GHz, 3.6cm) has been only sub-mas frame until last 10 years (e.g. Ma+, ICRF1, 1998, Ma+, ICRF2, 2009,)

**VLBI:**
- SX-band (8 GHz, 3.6cm) precision ~ 50 µas (Charlot et al, ICRF-3, 2018, in prep)
- K-band (24 GHz, 1.2cm) precision ~ 100 µas (Lanyi+, 2010; de Witt+, 2018)
- X/Ka-band (32 GHz, 9mm) precision ~ 100 µas (Jacobs+, 2018)

- Accuracy limited by VLBI systematics due to weak southern geometry, troposphere, etc. at 30 to 200 µas

**Optical**
- Gaia optical: Data Release #2 precision ~250 µas for radio loud quasars (Mignard+, 2018)

- Tie Precision is excellent allowing 3-D rotational alignment precision of ~15 µas
Celestial Frames using Radio Interferometry (VLBI)
Radio Interferometry: Long distance phased arrays

Very Long Baseline Interferometry is a type of station differenced range from a phased array

• Measures geometric delay by cross-correlating signal from two (2) stations

$$\tau = B \cdot \frac{s}{c}$$

10,000 km baselines give resolution of $$\frac{\lambda}{B} \sim$$ few nanoradian sub-mas beam !!

Resolves away all but galactic nucleus

Gaia beam $$\sim 60$$ mas
Radio Source Structure vs. Frequency

The sources become better \( \rightarrow \) Less structure

The goal:

Alignment of Optical and Radio into Common Frame
Frame Tie Comparisons
Tying Optical and Radio Celestial Frames

Systematics to be flushed out via Inter-comparison of multiple high precision frames.

Systematics:

Gaia: 60 mas beam sees Host galaxy, foreground stars, etc.

ALMA: pilot obs bright end ~5\text{mag}
Waiting on 10km+ configurations

VLBI: All bands need more southern data

S/X: Source structure
K: Ionosphere
XKa: Argentina baselines under-observed

Credit: Marscher+, Krichbaum+
SX (8 GHz, 3.6cm) \textit{ICRF-3}

- **Strengths:**
  - 4536 sources
  - Uniform spatial density
  - Median RA precision $\sim$40 $\mu$as
  - 40 years, 13 million obs averages many error down

- **Weaknesses:**
  - Source structure
  - South ($\delta < -30$ deg) weak due to limited South Africa-Australia data

Charlot et al et al, ICRF3, 2018, in prep
55% matches usable with Gaia, but five times more total matches than K or Ka. Weaker in the south. Gaps near galactic plane. Color code shows Gaia formal sigmas.
Tying optical and Radio Celestial Frames

Gaia DR2 vs. SX VLBI

Arc differences vs. arclength shows distortion at 5 μas level (2.4e-11)
Systematic tilt? $\Delta \delta$ vs. $\delta$ has 2 sigma slope of $-0.2 \pm 0.1$ $\mu$as/deg
**SX** (Charlot et al, 2018, in prep) vs. Gaia Optical Frame (Mignard+, 2018)

**Spherical Harmonic Differences for 2494 common sources (10% outliers removed)**

Largest terms ~ 30 μas (scheme of Mignard & Kiloner, 2012)

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>value</th>
<th>sigma</th>
<th>scaled σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 rotation_X =</td>
<td>16.634</td>
<td>+6.0223 μas</td>
<td>8.9072</td>
</tr>
<tr>
<td>R2 rotation_Y =</td>
<td>-16.298</td>
<td>+5.9627 μas</td>
<td>8.8192</td>
</tr>
<tr>
<td>R3 rotation_Z =</td>
<td>9.6995</td>
<td>+5.2049 μas</td>
<td>7.6983</td>
</tr>
<tr>
<td>Dipole-1 =</td>
<td>6.7523</td>
<td>+5.7940 μas</td>
<td>8.5696</td>
</tr>
<tr>
<td>Dipole-2 =</td>
<td>8.9083</td>
<td>+5.6332 μas</td>
<td>8.3317</td>
</tr>
<tr>
<td>Dipole-3 =</td>
<td>-6.5067</td>
<td>+5.7051 μas</td>
<td>8.4382</td>
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<tr>
<td>Quad 20 Mag R(sin2Dec)=</td>
<td>-1.0679</td>
<td>+5.8846 μas</td>
<td>8.7036</td>
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<tr>
<td>Quad 20 Elc R(sin2Dec)=</td>
<td>-32.995</td>
<td>+6.4831 μas</td>
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<tr>
<td>Quad 21 Elc Real =</td>
<td>2.6989</td>
<td>+8.1422 μas</td>
<td>12.043</td>
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<tr>
<td>Quad 21 Elc Imag =</td>
<td>-29.171</td>
<td>+8.2085 μas</td>
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<td>Quad 21 Mag Real =</td>
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<td>+7.5641 μas</td>
<td>11.188</td>
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<tr>
<td>Quad 21 Mag Imag =</td>
<td>-18.812</td>
<td>+7.8110 μas</td>
<td>11.553</td>
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<tr>
<td>Quad 22 Elc Real =</td>
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<td>+3.7016 μas</td>
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<tr>
<td>Quad 22 Elc Imag =</td>
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<tr>
<td>Quad 22 Mag Real =</td>
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<td>+3.6390 μas</td>
<td>5.3822</td>
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<tr>
<td>Quad 22 Mag Imag =</td>
<td>3.9390</td>
<td>+3.6769 μas</td>
<td>5.4383</td>
</tr>
</tbody>
</table>

Diagonal covariance
**K (24 GHz, 1.2cm)**  **VLBA+ (HartRAO-Hobart)**

- **Strengths:**
  - Uniform spatial density, 824 sources
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - median RA/Dec precision ~40 / 80 µas
  - needed ~ 0.5 million observations vs. SX’s 13 million!

- **Weaknesses:**
  - Ionosphere only partially calibrated by GPS.
  - South (δ < -30 deg) weak due to limited South Africa-Tasmania data

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**De Witt et al, 2018**  
astrometric solution D. Gordon

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2018 Oct 10, C.S. Jacobs
Tying optical and Radio Celestial Frames

Gaia-DR2 vs. K (24 GHz) VLBI

Fairly uniform distribution. 65% usable matches with Gaia
Color code shows unevenness in Gaia formal sigmas.
Tying optical and Radio Celestial Frames

Gaia DR2 vs. K VLBI

Arc differences vs. arclength shows distortion at 10-20 \( \mu \text{as} \) level (0.5 to 1.e-10)
Tying optical and Radio Celestial Frames

Gaia DR2 vs. K VLBI

Systematic tilt: $\Delta \delta$ vs. $\delta$ has 6 sigma slope of 1.25 $\pm$ 0.2 $\mu$as/deg
**K (de Witt et al, 2018) vs. Gaia Optical Frame (Mignard+, 2018)**

**Spherical Harmonic Differences for 535 common sources (10% outliers removed)**

Largest term $-84$ µas (Diagonal covariance)

<table>
<thead>
<tr>
<th>Parameter_name</th>
<th>value</th>
<th>sigma</th>
<th>scaled $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 rotation_X</td>
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<td>15.410</td>
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<tr>
<td>R2 rotation_Y</td>
<td>8.5640</td>
<td>10.097</td>
<td>15.307</td>
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<td>R3 rotation_Z</td>
<td>3.4207</td>
<td>8.2059</td>
<td>12.441</td>
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<tr>
<td>Dipole-1</td>
<td>26.536</td>
<td>9.5931</td>
<td>14.544</td>
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<tr>
<td>Dipole-2</td>
<td>-51.492</td>
<td>9.5940</td>
<td>14.545</td>
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<td>Dipole-3</td>
<td>-24.847</td>
<td>9.0398</td>
<td>13.705</td>
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<td>Quad 20 Mag R(sin2Dec)</td>
<td>27.345</td>
<td>9.2511</td>
<td>14.025</td>
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<tr>
<td>Quad 20 Elc R(sin2Dec)</td>
<td>-23.277</td>
<td>10.754</td>
<td>16.304</td>
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<tr>
<td>Quad 21 Elc Real</td>
<td>17.858</td>
<td>12.701</td>
<td>19.255</td>
</tr>
<tr>
<td>Quad 21 Elc Imag</td>
<td>61.432</td>
<td>13.110</td>
<td>19.876</td>
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<tr>
<td>Quad 21 Mag Real</td>
<td>-83.783</td>
<td>12.348</td>
<td>18.720</td>
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<tr>
<td>Quad 21 Mag Imag</td>
<td>-5.2426</td>
<td>12.781</td>
<td>19.377</td>
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<tr>
<td>Quad 22 Elc Real</td>
<td>8.3740</td>
<td>5.7978</td>
<td>8.7898</td>
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<tr>
<td>Quad 22 Elc Imag</td>
<td>19.566</td>
<td>5.7173</td>
<td>8.6677</td>
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<tr>
<td>Quad 22 Mag Real</td>
<td>-24.686</td>
<td>5.6310</td>
<td>8.5369</td>
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<tr>
<td>Quad 22 Mag Imag</td>
<td>1.6044</td>
<td>5.7419</td>
<td>8.7050</td>
</tr>
</tbody>
</table>
Ka (32 GHz, 9mm) Combined NASA/ESA Network

- **Strengths:**
  - Uniform spatial density, 678 sources
  - Less structure than S/X (3.6cm)
  - Precision < 100 μas
  - Needed only 70K observations vs. SX’s 12 million!

- **Weaknesses:**
  - Poor near Galactic center due to interstellar media scattering
  - South weak due to limited time on ESA’s Argentina station
  - Limited Argentina-California data makes vulnerable to δ zonals
  - Limited Argentina-Australia weakens δ from -45 to -60 deg
Tying optical and Radio Celestial Frames
Gaia-DR2 vs. Ka (32 GHz) VLBI

67% usable matches. Fairly uniform distribution except near galactic plane
Color code shows Gaia formal sigmas.
Tying optical and Radio Celestial Frames

Ka VLBI vs. Gaia DR2

Arc differences vs. arclength bins scatter at 15-30 μas level
Tying optical and Radio Celestial Frames

**Ka VLBI vs. Gaia DR2**

\[ \Delta \alpha \cos \delta \sim \sin(2 \, \delta) \quad \text{Quadrupole 2,0} \]

\[ \Delta \delta \sim \cos(\delta) \quad \text{z-dipole} \]
Spherical Harmonic Differences for 454 common sources (10% outliers removed)

With Diagonal covariance only

<table>
<thead>
<tr>
<th>Parameter_name</th>
<th>value</th>
<th>sigma</th>
<th>scaled σ</th>
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<tbody>
<tr>
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<td>13.871</td>
<td>11.366</td>
<td>18.100</td>
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<td>R2 rotation_Y</td>
<td>-7.6911</td>
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<td>19.225</td>
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<td>R3 rotation_Z</td>
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<td>9.4541</td>
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<td>Dipole-1</td>
<td>19.008</td>
<td>15.100</td>
<td>24.047</td>
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<td>Dipole-2</td>
<td>-22.924</td>
<td>14.795</td>
<td>23.562</td>
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<tr>
<td>Dipole-3</td>
<td>201.00</td>
<td>47.962</td>
<td>76.381</td>
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<tr>
<td>Quad 20 Mag R(sin2Dec)=</td>
<td>-211.23</td>
<td>18.148</td>
<td>28.902</td>
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<tr>
<td>Quad 20 Elc R(sin2Dec)=</td>
<td>-77.057</td>
<td>24.744</td>
<td>39.406</td>
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<tr>
<td>Quad 21 Elc Real</td>
<td>76.938</td>
<td>18.087</td>
<td>28.805</td>
</tr>
<tr>
<td>Quad 21 Elc Imag</td>
<td>-99.147</td>
<td>17.774</td>
<td>28.305</td>
</tr>
<tr>
<td>Quad 21 Mag Real</td>
<td>-51.417</td>
<td>13.944</td>
<td>22.206</td>
</tr>
<tr>
<td>Quad 21 Mag Imag</td>
<td>-59.487</td>
<td>14.447</td>
<td>23.007</td>
</tr>
<tr>
<td>Quad 22 Elc Real</td>
<td>19.839</td>
<td>6.7002</td>
<td>10.670</td>
</tr>
<tr>
<td>Quad 22 Elc Imag</td>
<td>0.38448</td>
<td>6.9835</td>
<td>11.122</td>
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<tr>
<td>Quad 22 Mag Real</td>
<td>-1.4474</td>
<td>6.3603</td>
<td>10.129</td>
</tr>
<tr>
<td>Quad 22 Mag Imag</td>
<td>-14.130</td>
<td>6.3945</td>
<td>10.184</td>
</tr>
</tbody>
</table>
Ka-band combined NASA/ESA Deep Space Net

ESA Argentina to NASA-California under-observed by order of magnitude!

Baseline percentages

- Argentina is part of 3/5 baselines or 60% but only 14% of obs
- Aust- Argentina 7.4%
- Spain-Argetina 2.4%
- Calif- Argentina 3.7%

This baseline is under-observed by a factor of ~ 12.

More time on ESA’s Argentina station would have a huge, immediate impact!!

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
# Tying optical and Radio Celestial Frames

## Gaia DR2 vs. VLBI

<table>
<thead>
<tr>
<th></th>
<th>SX-band 8 GHz 3.6 cm</th>
<th>K-band 24 GHz 1.2 cm</th>
<th>XKa-band 32 GHz 0.9 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td># Observations</td>
<td>13 million</td>
<td>0.5 million</td>
<td>0.07 million</td>
</tr>
<tr>
<td># matched sources</td>
<td>2818</td>
<td>601</td>
<td>499</td>
</tr>
<tr>
<td># outliers &gt; 5(\sigma)</td>
<td>325</td>
<td>67</td>
<td>45</td>
</tr>
<tr>
<td>% outliers</td>
<td>11.5 %</td>
<td>11.1 %</td>
<td>9.0 %</td>
</tr>
<tr>
<td>(\alpha) wRMS</td>
<td>305 (\mu)as</td>
<td>219 (\mu)as</td>
<td>259 (\mu)as</td>
</tr>
<tr>
<td>(\delta) wRMS</td>
<td>315 (\mu)as</td>
<td>241 (\mu)as</td>
<td>276 (\mu)as</td>
</tr>
<tr>
<td>(R_x)</td>
<td>17 +- 9</td>
<td>35 +- 15</td>
<td>14 +- 19</td>
</tr>
<tr>
<td>(R_y)</td>
<td>-16 +- 9</td>
<td>9 +- 12</td>
<td>-8 +- 19</td>
</tr>
<tr>
<td>(R_z)</td>
<td>10 +-13</td>
<td>3 +- 12</td>
<td>-19 +- 15</td>
</tr>
<tr>
<td>Largest Vector Spherical Harmonic</td>
<td>-33 +- 10 (\mu)as Quad 2,0 E</td>
<td>-84 +- 19 (\mu)as Quad 2,1 M</td>
<td>-211 +- 29 (\mu)as Quad 2,0 M</td>
</tr>
</tbody>
</table>
Summary: Tying Optical & Radio

• **Goal:** Tie of optical and radio celestial frames for deep space navigation and astronomical applications.

• **Results:**
  
  — Optical & radio data now allow multi-wavelength comparisons: Radio at 8, 24, 32 GHz and Gaia optical
  
  — Excellent 3-D rotational tie at 20 µas level.
  
  — Accuracy limited by systematic distortions at 30 – 300 µas.
  
  — SX (8 GHz) ~30 µas, K (24) 80 µas, Ka (32) 300 µas.
  
  — Control of VLBI systematics will require increased southern observations at all bands.
  
  — Gaia precision limited by partial mission. More data to come . . .
  
  — Gaia DR3 will add significantly more data and model non-linear motions
BACKUP
The Gaia Optical Frame
ESA’s Gaia optical Astrometry

- **Method**: extremely accurate centroid of 60 mas pixels. Compare to VLBI sub-mas beam.

- **Astrometry & photometric survey to V = 20.7mag**
  - ~10^9 objects: stars, QSOs, solar system, galaxies.

- **Gaia Celestial Reference Frame (GCRF):**
  - Optically bright objects (V< 18mag) give best precision
  - 2nd release Gaia astrometric catalog DR2 Apr 2018,
  - DR3 2020.

Credit: F. Mignard (2013)

**Anticipated precision of Gaia catalogue**

**Gaia Data Release-2:**

Precision ~ 250 μas for radio loud quasars
Tying optical and Radio Celestial Frames

Gaia DR2 vs. SX (8 GHz) VLBI

Median = −10.942 µas
Mean = −6.939 µas
\( \text{wRMS}_\mu = 304.980 \text{ µas} \)

Median = −7.700 µas
Mean = −12.320 µas
\( \text{wRMS}_\mu = 313.377 \text{ µas} \)

wRMS Ra and Dec differences about 300 µas (1.5 nrad)
Tying optical and Radio Celestial Frames

Gaia DR2 vs. K (24 GHz) VLBI

wRMS Ra and Dec differences about 230 μas (1.1 nrad)
Tying optical and Radio Celestial Frames

Gaia DR2 vs. Ka (32 GHz) VLBI

wRMS Ra and Dec differences about 270 μas (1.3 nrad)
Optical vs. Radio systematics offsets
SDSS Optical images of quasars (scale 5-10 asec)

- Optical structure: The host galaxy may not be centered on the AGN or may be asymmetric.
- Optical systematics unknown, fraction of millarcsecond optical centroid offset?
- Optical imaging generally 10s of milliarcsecond. In general, no sub-mas optical imaging.

Credit: SDSS
Three VLBI bands compare to better than 200 μas RMS Gaia DR-2 precision ~ 250 μas.

**Zonal Errors**

- ΔRA vs. Dec:
  ~300 μas in south, 200 μas in north

- Need 2 baselines to get 2 angles:
  California-Canberra: 24K obs
  California-Argentina: 2K obs

- Need more California-Argentina data to overcome this 12 to 1 distortion in sampling geometry. ESA’s Malargüe is key.

- Usuda, Japan 54-m XKa (2019) would improve North-South sampling geometry and thus control declination zonal differences.
The Source

Objects
Optical-Radio Frame Tie Geometry

Determine 3 small rotations ($R_{1,2,3}$) and zonal differences i.e. spherical harmonics $Y_{lm}$ between the individually rigid, non-rotating radio and optical frames to sub-part per billion level

Allows seamless integration into united frame.

More than 1 billion objects will be integrated into common frame!!

Object precision to < 100 μas, 0.5 ppb. want tie errors 10 times smaller.

Radio (VLBI) Frame is current official IAU definition of $\alpha$, $\delta$

Used for Nav trajectories, JPL planetary ephemeris, Earth Orientation... essentially everything

Gaia optical frame will be a rigid non-rotating frame also based on quasars Also of sub-ppb precision
What objects can we use?
Methods for Tying Optical and Radio Celestial Frames

- Need common objects well measured in both optical and radio

- **Radio stars:** Previous generation used galactic stars that emit in radio,
  crude by today’s standards: difficult to achieve desired accuracy level.
  e.g. Lestrade et al. (1995).

- **Thermal emission from regular stars:**
  350 GHz astrometry using Atacama Large Millimeter Array (ALMA)
  Fomalont et al. (pilot observations)
  Verifies bright end of optical, but likely limited to 500 – 1000 µas (2.5 to 5 ppb).

- **Extra-galactic Quasars:** detectable in both radio and optical
  potential for better than 100 µas to 20 µas (0.5 to 0.1 ppb).

  **Strengths:** extreme distances (> 1 billion light years) means no parallax or proper motion
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

Features of AGN: Note the Logarithmic length scale.

“Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core.”


Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)
K-band (24 GHz) imaging shows VLBI sources are compact on millarcsec scales. Data for 500+ sources acquired. Processing limited by available analyst resources. Imaging will be prioritized as comparison outliers pinpoint sources of interest.

The authors gratefully acknowledge use of the Very Long Baseline Array under the US Naval Observotory's time allocation. This work supports USNO's ongoing research into the celestial reference frame and geodesy.
Example Extragalactic Source: Centaurus-A in X-ray, Optical, Radio