The Power of Multi-Frequency Observations at mm-waves:

Astrometry up to 132 GHz with the KVN

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Overview

• A mm-VLBI Astrometric Method: Source Frequency Phase Referencing
  ➔ Outcomes: 1) Effective Atmospheric/Instr. Compensation, 2) Astrometry (up to 132 GHz) and 3) Increased Coherence

• Demonstration with 4-bands KVN observations, up to 132 GHz (continuum)

• From Relative to Individual Source Shifts for Image Alignment (NEW)

• (Brief) Astrophysical Applications
Frequency Phase Referencing (FPT)

WEAK SOURCES ASTROMETRY

Target Source @low&high freq.

Bet ter simultaneous! Higher frequencies ok

\[ R = \frac{\nu}{\nu} \]

Fast \[ \phi_{A,FPT} = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A \]

Non-dispersive Errors:

\[ \phi_{A,TRO} - R \cdot \phi_{A,TRO} = 0 \]

\[ \phi_{A,GEO} - R \cdot \phi_{A,GEO} = 0 \]

Dispersive Errors:

\[ \phi_{A,ION} - R \cdot \phi_{A,ION} = (R-1/R) \cdot \phi_{A,ION} \]

\[ \phi_{INST} \ldots \text{Anything!} \]

Multi-channel KVN receivers
OUTCOME: PRECISE CALIBRATION OF THE TROPOSPHERE
(and in general any non-dispersive residuals)

ENABLES: EXTEND COHERENCE TIME

→ WEAK SOURCE DETECTION AT HIGH FREQUENCIES
→ ASTROMETRY

* SIMULTANEOUS multi-frequency observations required for high freqs.
Source Frequency Phase Referencing (SFPR)

WEAK SOURCES ASTROMETRY

BETTER SIMULTANEOUS! HIGHER FREQUENCIES OK

Target Source A

Several deg.

Reference Source B

Several Minutes

\( R = \nu / \nu \)

\( \phi_A - \phi_B = 0 \)

\( \phi_A,\text{INST} - \phi_B,\text{INST} = 0 \)

FPT

\( \phi_{A,\text{ION}} - \phi_{B,\text{ION}} = 0 \)

\( \phi_{A,\text{STR}} + 2\pi n_A \)

\( \phi_{B,\text{STR}} + 2\pi n_B \)

Fast

\( \phi_{A,\text{ION}} + \phi_{B,\text{ION}} + \phi_{A,\text{TRO}} + \phi_{B,\text{TRO}} + \phi_{A,\text{GEO}} + \phi_{B,\text{GEO}} + 2\pi n_A \)

\( \phi_{B,\text{GEO}} + \phi_{B,\text{TRO}} + \phi_{B,\text{GEO}} + 2\pi n_B \)

KVN Multi-Channel Receiver Optical Bench

KVN Multi-Channel Receiver Optical Bench

\( \phi_{A,B} \text{ SFPR} \leftrightarrow \text{ FFT} \)

KVN

SFPRed A-Map at high freq.
Source Frequency Phase Referencing (SFPR)

WEAK SOURCES
ASTROMETRY


Target Source A

Several deg.

Reference Source B

\[ \phi_{A-B}^{SFPR} = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A \]

\[ \phi_{B}^{FPT} = \phi_{B,GEO} + \phi_{B,TRO} + \phi_{B,ION} + \phi_{B,INST} + \phi_{B,STR} + 2\pi n_B \]

\[ \phi_{A,ION} = \phi_{B,ION} = 0 \]

\[ \phi_{A,INST} - \phi_{A,INST} = 0 \]

BETTER SIMULTANEOUS! (TWO SOURCES)
HIGHER FREQUENCIES OK

R = \nu / \nu

KVN Multi-Channel Receiver Optical Bench

SFPR:
Rioja & Dodson 2008, 2011

KVN

SFPRed A-Map at high freq.

Astrometry:
OUTCOME: PRECISE ATMOSPHERIC & INSTR. CALIBRATION, WHILE KEEPING ASTROMETRIC SIGNATURE

ENABLES: EXTEND COHERENCE TIME & ASTROMETRY

» WEAK SOURCE DETECTION AT HIGH FREQUENCIES

» ASTROMETRY (frequency dependent source position: continuum & lines)

* Slow antenna switching OK
* Several degrees source separation OK
* SIMULTANEOUS multi-frequency observations required for high freqs.
Demonstration: 4-band KVN SFPR observations of 5 AGNs

22, 43, 86, 129 GHz
Demonstration: 4-band KVN SFPR observations of 5 AGNs

Triangle 1
Triangle 2

22, 43, 86, 129 GHz
Demonstration: 4-band KVN SFPR observations of 5 AGNs

Triangle 1
Triangle 2

22, 44, 88, 132 GHz
KVN Obs.: Duration 8 hours 3 min scan/source
Demonstration: 4-band KVN SFPR observations of 5 AGNs

Triangle 1
Triangle 2

22, 44, 88, 132 GHz

KVN Obs.:
Duration 8 hours
3 min scan/source
(1) Outcomes: Effective Tropospheric Compensation

FPT analysis – “2-frequencies”
Residuals increase with $R$, for a given $\nu_{\text{low}}$ (22GHz).

FPT: $22 \rightarrow 44$, x2
FPT analysis – "2-frequencies"

Residuals increase with \( R \), for a given \( \nu \) low (22GHz)

FPT: 22 \( \rightarrow \) 44, x2

FPT: 22 \( \rightarrow \) 88, x4
Residuals increase with R, for a given $\nu_{low}$ (22 GHz).
FPT analysis – “2-frequencies”
Residuals increase with $R$, for a given $\nu_{\text{low}} (44 \text{ GHz})$
FPT analysis – “2-frequencies”

Residuals increase with $R$, for a given $\nu_{\text{low}}$ (44 GHz)

$$\phi_A = \phi_{\text{GEO}} + \phi_{\text{TRO}} + \phi_{\text{ION}} + \phi_{\text{INST}} + 2\pi n_A$$

$$R = \nu / \nu$$

Dispersive Terms non-zero, preventing imaging, but not fast changing
(1) Outcomes: Effective Tropospheric Compensation

**FPT analysis – “2-frequencies”**

(2) Outcomes: Astrometry

**SFPR analysis – “2-frequencies” & “2 sources”**
SFPR analysis – 132 GHz with 43GHz: 2007+777 (ref. 6.3° away)

A) 2007+777, FPT, 44→132, x3

B) ref., FPT, 44→132, x3

A) SFPR, 132 GHz

Bona-fide Astrometry Shift ~ (-50,+50) μas

Peak Flux ~ 150 mJy
rms ~ 5mJy/beam
85-90% Flux Recovery
SFPR analysis – 132 GHz with 43GHz: 2007+777 (ref. 6.3° away)

A) 2007+777, FPT, 44→132, x3

B) ref., FPT, 44→132, x3

A) SFPR, 132 GHz

A) – B)

2007+777 at 132 GHz (with ref. source 6.3° away)

No direct detections at 132 GHz

Astrometric Error ~ 30 μas

A) SFPRed Map at 132 GHz

Bona-fide Astrometry Shift ~ (-50,+50) μas

Peak Flux ~ 150 mJy
rms ~ 5mJy/beam
85-90% Flux Recovery
SFPR analysis – 132 GHz with 43GHz: 1842+681 (ref. 11° away)

A) 1842+681 FPT, 44→132, x3

B) ref., FPT, 44→132, x3

A) SFPR 132 GHz

A) SFPRed Map at 132 GHz

Bona-fide Astrometry Shift ~ (-221, +150) μas

Peak Flux ~ 100 mJy
rms ~ 5 mJy/beam
87% Flux Recovery

FFT
SFPR analysis – 132 GHz with 43GHz: 1842+681 (ref. 11° away)

No direct detections at 132 GHz (with ref. source 11° away)

A) 1842+681 FFT, 44⇒132, x3

B) ref., FPT, 44⇒132, x3

A) SFPR 132 GHz

Peak Flux ~ 100 mJy
rms ~ 5 mJy/beam
87% Flux Recovery

Bona-fide Astrometry Shift ~ (-221, +150) μas

A - B

No direct detections - 50 μas

Bona-fide Astrometry

Shil ~ (-221, +150) μas

Peak Flux ~ 100 mJy
rms ~ 5 mJy/beam
87% Flux Recovery
SFPR Astrometric RELATIVE Measurements: between TWO frequencies & TWO sources

- Red-KQ
- Blue KW
- Black KD
- Green QW
- Cyan QD
(1) Outcomes: Effective Tropospheric Compensation
\[ \text{FPT analysis – “2-frequencies”} \]

(2) Outcomes: Astrometry
\[ \text{SFPR analysis – “2-frequencies” & “2 sources”} \]

(3) Outcomes: Increased Coherence Time
\[ \text{FPT & SFPR analysis} \]
Demonstration: Coherence Studies

<table>
<thead>
<tr>
<th>Freq.Pair</th>
<th>Analysis</th>
<th>Effective Coherence Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 → 132 GHz</td>
<td>FPT (or MFPR)</td>
<td>20 min</td>
</tr>
<tr>
<td>44 → 132 GHz</td>
<td>SFPR (*11deg)</td>
<td>&gt; 8 hours</td>
</tr>
</tbody>
</table>

Coherence Measurements at 129 GHz

- % Peak Flux Recovery
- Time (minutes)

FPT
- 20min
- 8 hours

SFPR
- 60%
NEW: From Relative to Individual Source Shifts: Single Value Decomposition Method

\[ \nu_{\text{low}} \rightarrow \nu_{\text{high}} \]

θ Position shift

1, 2, 3, 4, 5 sources

\[
\begin{bmatrix}
\theta_{12} \\
\theta_{13} \\
\theta_{23} \\
\theta_{14} \\
\theta_{15} \\
\theta_{45}
\end{bmatrix}
\begin{bmatrix}
1 & -1 & 0 & \ldots \ldots \\
1 & 0 & -1 & \ldots \ldots \\
0 & 1 & -1 & \ldots \ldots \\
. & . & \ldots \ldots \\
. & . & \ldots \ldots \\
. & . & \ldots \ldots \\
\end{bmatrix}
\begin{bmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4 \\
\theta_5
\end{bmatrix}
\]

SVD

\[ [S] \]

Degenerate Solution

[A-B] = [M] x [S]

Astrometric Relative Measurements

Source Pair Matrix

Individual Source Shifts
Individual Source Shifts: Single Value Decomposition Method

Degenerate Solution

1803
1807
1842

1928
2007

Red KQ
Blue KW
Cyan KD
Green QW
Black QD
In the maps:

RA

In the plots:

RA
• Independent analysis per frequency pair
• PLOT: Unique common shift \((x=\text{RA}, y=\text{DEC})\) for all 5 sources, and combined (all-sources) Misalignment with corresponding Jet Directions \((z=\text{Error})\).
• More sources and wider distribution of PAs sets stronger constraints.
Individual Source Shifts: Single Value Decomposition Method
PLUS Jet Direction Constraint

Red KQ
Blue KW
Cyan KD
Green QW
Black QD

Jet Directions

Non-Degenerate Solution

1803
1807
1842
1928
2007
1803, 2007
1928
1842
1807
Individual Source Shifts: Single Value Decomposition Method
PLUS Jet Direction Constraint

Non-Degenerate Solution

Jet Directions

Next: Ready for image alignment at the four frequency bands
Any field that requires mm-wave:
1) bona-fide astrometric image alignment at different frequencies, and/or
2) increased sensitivity.

- Spatial registrations of molecular emission in Evolved Stars and SFRs (see talk by Yun Youngjoo; poster by Yoon Dong-Hwan et al., \(H_2O\) and SiO)

- AGN Core-Shifts at mm-waves: transition from BK model to shock.

- Spectral Index and Rotation Measure Maps.

- With multiple bands, one can measure the Spectral Energy Distribution and perform Faraday Tomography.
Bona-fide Astrometric Measurements between 5 AGNs at 132 GHz.

Demonstration of capabilities with KVN observations up to 132 GHz.

Made possible by the SFPR method → high precision astrometry with mm-VLBI, for continuum & spectral line.

A path for disentangling the measurements into the frequency dependent position shifts for the individual sources.

This is the basis for any study that requires alignment of mm-VLBI images at different frequencies.