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

Astrometry up to 132 GHz with the KVN

International Centre for Radio Astronomy Research

Maria J. Rioja, Richard Dodson,
ICRAR (Australia)
Taehyun Jung & Bong Won Sohn
KASI (Korea)

Curtin University

The University of Western Australia

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)

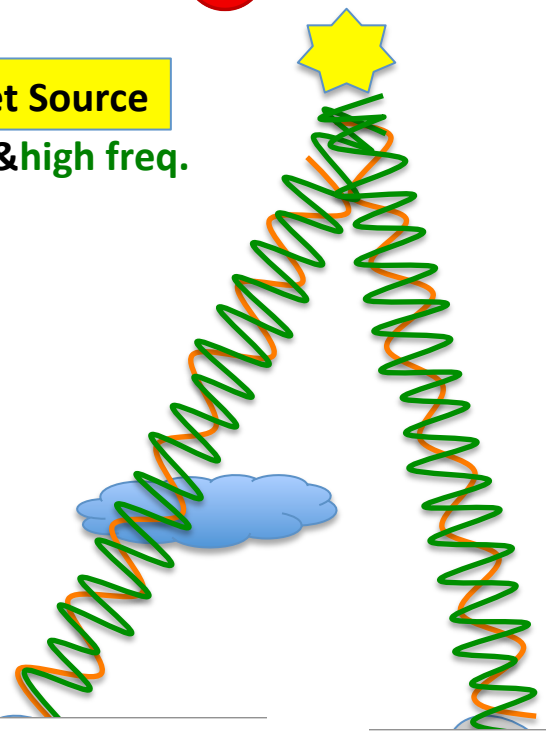
- From Relative to Individual Source Shifts for Image Alignment (NEW)

- (Brief) Astrophysical Applications

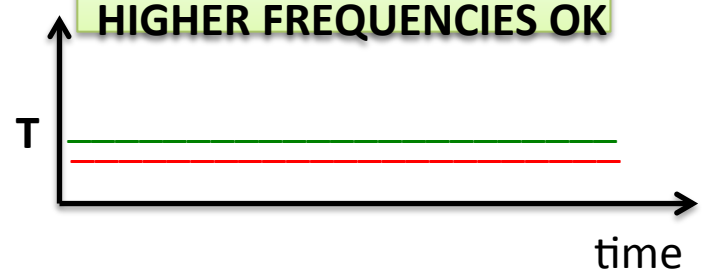
Frequency Phase Referencing (FPT)

WEAK SOURCES
ASTROMETRY

Target Source
@low&high freq.



BETTER SIMULTANEOUS!
HIGHER FREQUENCIES OK



$R = \nu / \nu$

Fast Slow Slow

$\phi_A^{FPT} = \phi_{A,GEO} + \phi_{A,TRO} - \phi_{ION} + \phi_{INST} + \phi'_{A,STR} + 2\pi n_A$

$R*\phi_A = R*(\phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A)$

Non-dispersive Errors:

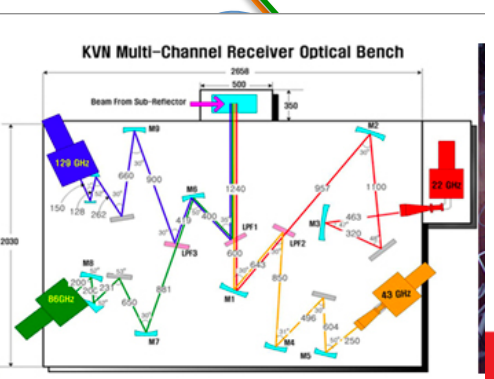
$\phi_{A,TRO} - R * \phi_{A,TRO} = 0$

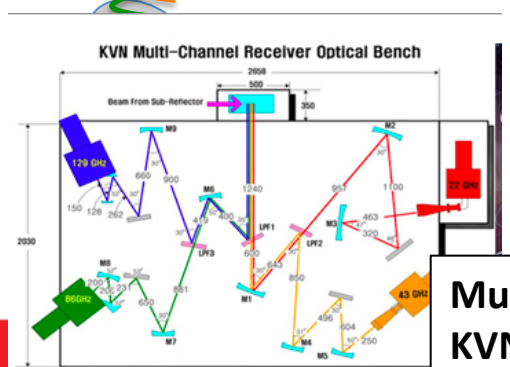
$\phi_{A,GEO} - R * \phi_{A,GEO} = 0$

Dispersive Errors:

$\phi_{A,ION} - R * \phi_{A,ION} = (R-1/R) * \phi_{A,ION}$

ϕ_{INST} ... Anything!





Multi-channel KVN receivers

Korea Astronomy and Space Science Institute

Frequency Phase Referencing (FPT)

(Also referred to as Multi Frequency Phase Referencing, MFPR)

OUTCOME: **PRECISE CALIBRATION OF THE TROPOSHERE**
(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.***

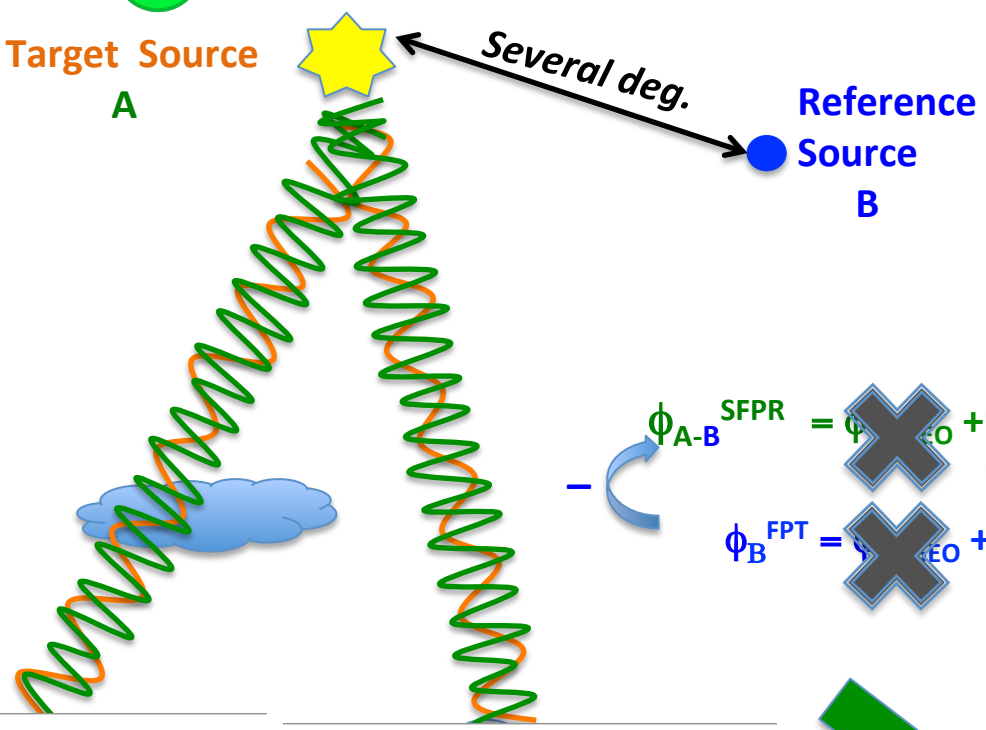
Source Frequency Phase Referencing (SFPR)

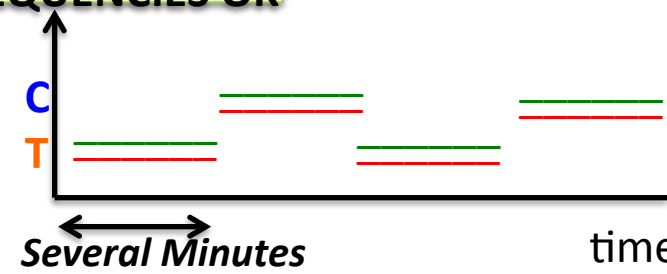
Rioja & Dodson 2008,2011

WEAK SOURCES ✓
ASTROMETRY ✓

BETTER SIMULTANEOUS!
HIGHER FREQUENCIES OK

(TWO SOURCES)





$R = \nu / \nu$

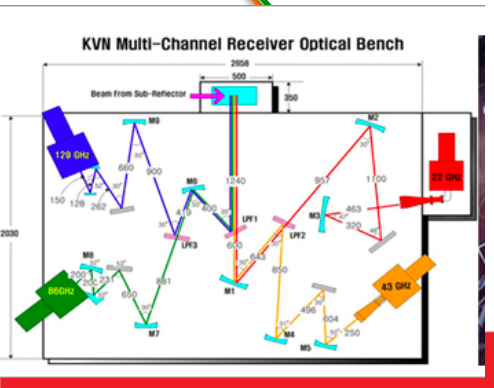
Fast Slow Slow

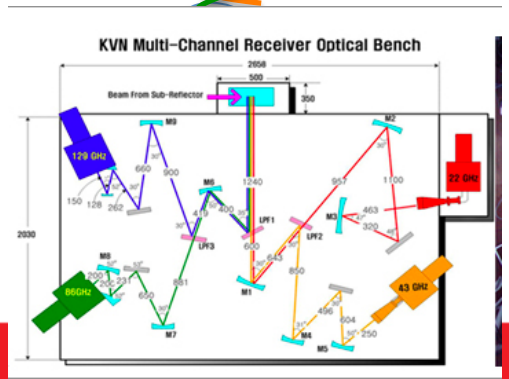
$\phi_{A-B}^{SFPR} = \phi_{GEO} + \phi_{ATM} + \phi_{ION} + \phi_{INST} + \phi''_{A,STR} + 2\pi n_A$

$\phi_B^{FPT} = \phi_{GEO} + \phi_{ATM} + \phi_{B,ION} + \phi_{B,INST} + \phi'_{B,STR} + 2\pi n_B$

$\phi_{A,ION} - \phi_{B,ION} = 0$

$\phi_{A,INST} - \phi_{A,INST} = 0$





KVN

Astrometry:

$\phi_{A-B}^{SFPR} \xleftrightarrow{FFT}$ **SFPRed A-Map at high freq.**

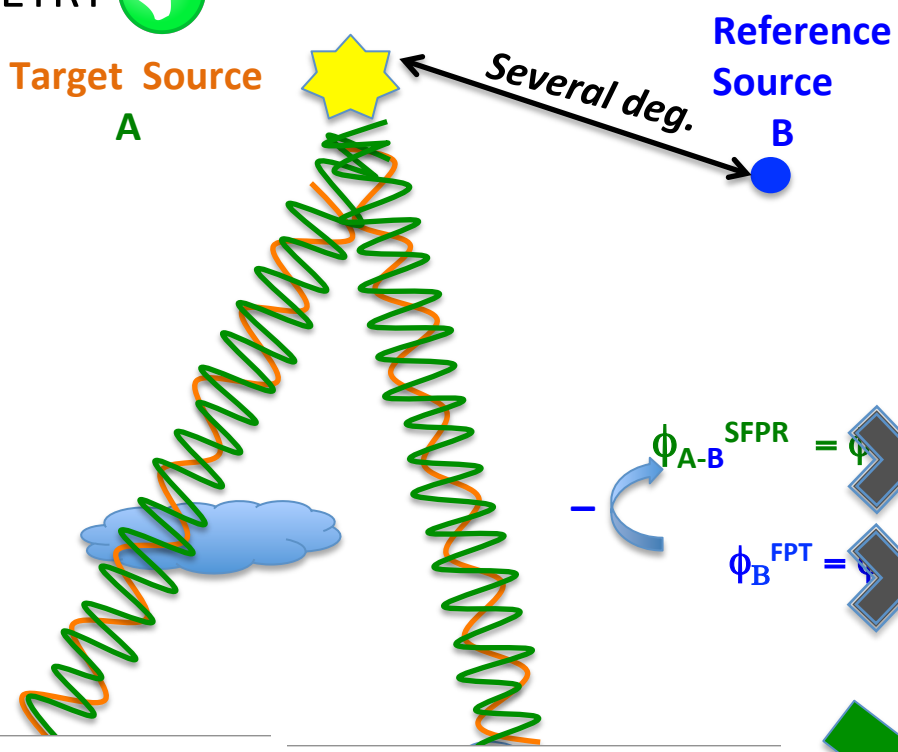
Korea Astronomy and Space Science Institute

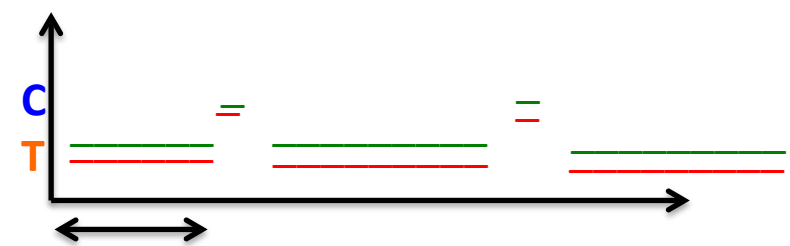
Source Frequency Phase Referencing (SFPR)

SFPR: Rioja & Dodson 2008,2011

WEAK SOURCES ✓
ASTROMETRY ✓

BETTER SIMULTANEOUS! (TWO SOURCES)
HIGHER FREQUENCIES OK





$R = \nu / \nu$

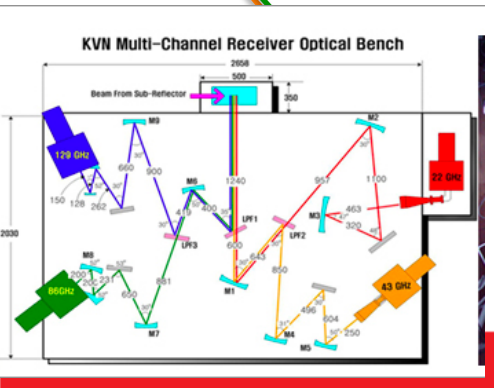
Fast Slow Slow

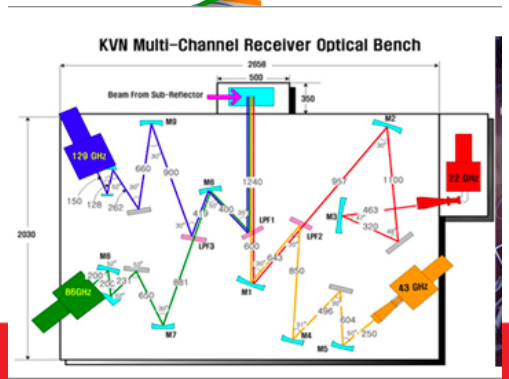
$\phi_{A-B}^{SFPR} = \phi_{GEO} + \phi_{ATM} + \phi_{ION} + \phi_{INST} + \phi''_{A,STR} + 2\pi n_A$

$\phi_B^{FPT} = \phi_{GEO} + \phi_{ATM} + \phi_{B,ION} + \phi_{B,INST} + \phi'_{B,STR} + 2\pi n_B$

$\phi_{A,ION} - \phi_{B,ION} = 0$

$\phi_{A,INST} - \phi_{A,INST} = 0$





KVN

Astrometry:

$\phi_{A-B}^{SFPR} \xleftrightarrow{FFT}$ **SFPRed A-Map at high freq.**

Korea Astronomy and Space Science Institute

Source Frequency Phase Referencing (SFPR)

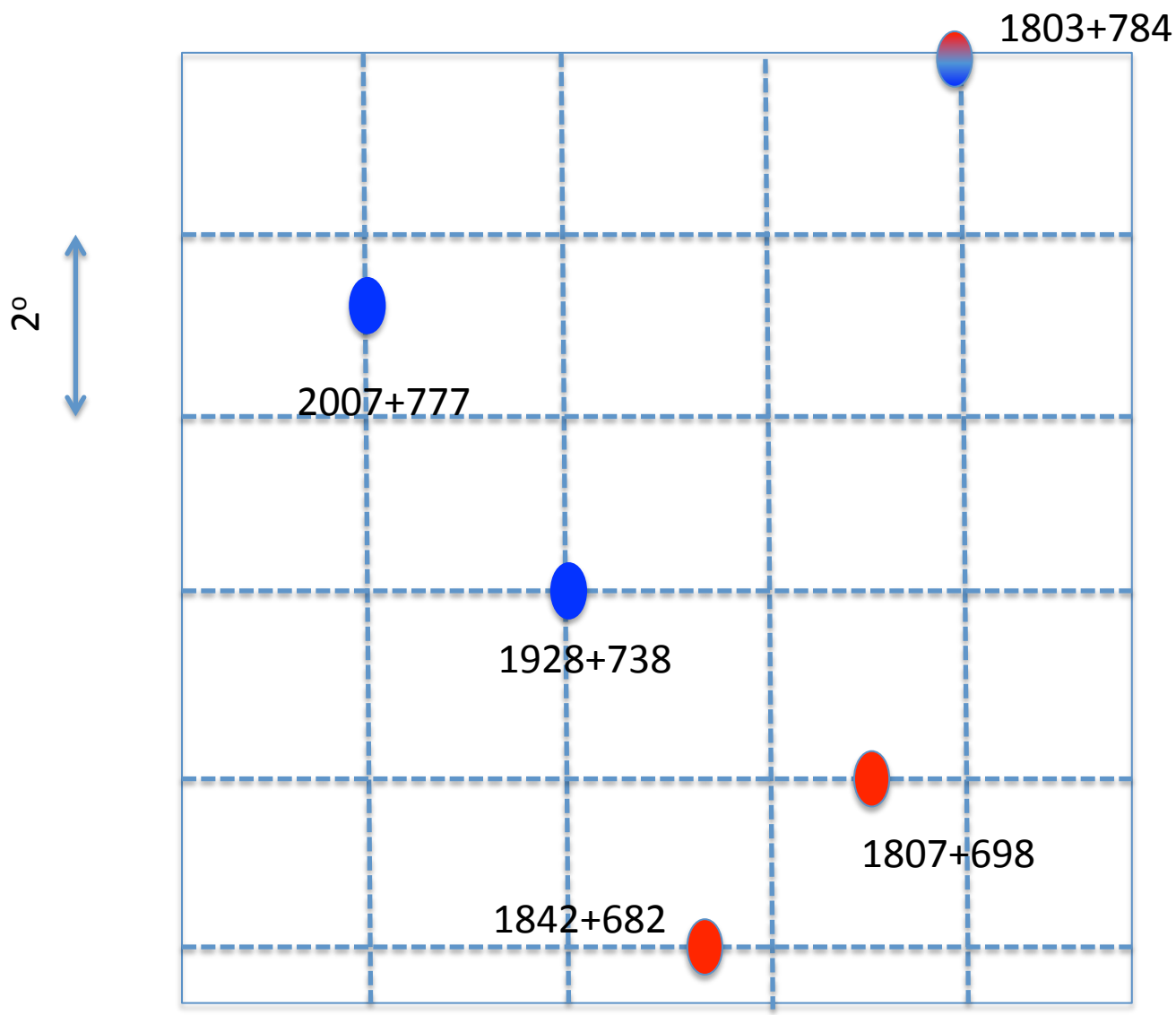
OUTCOME: **PRECISE ATMOSPHERIC & INSTR. CALIBRATION, WHILE KEEPING ASTROMETRIC SIGNATURE**

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.***

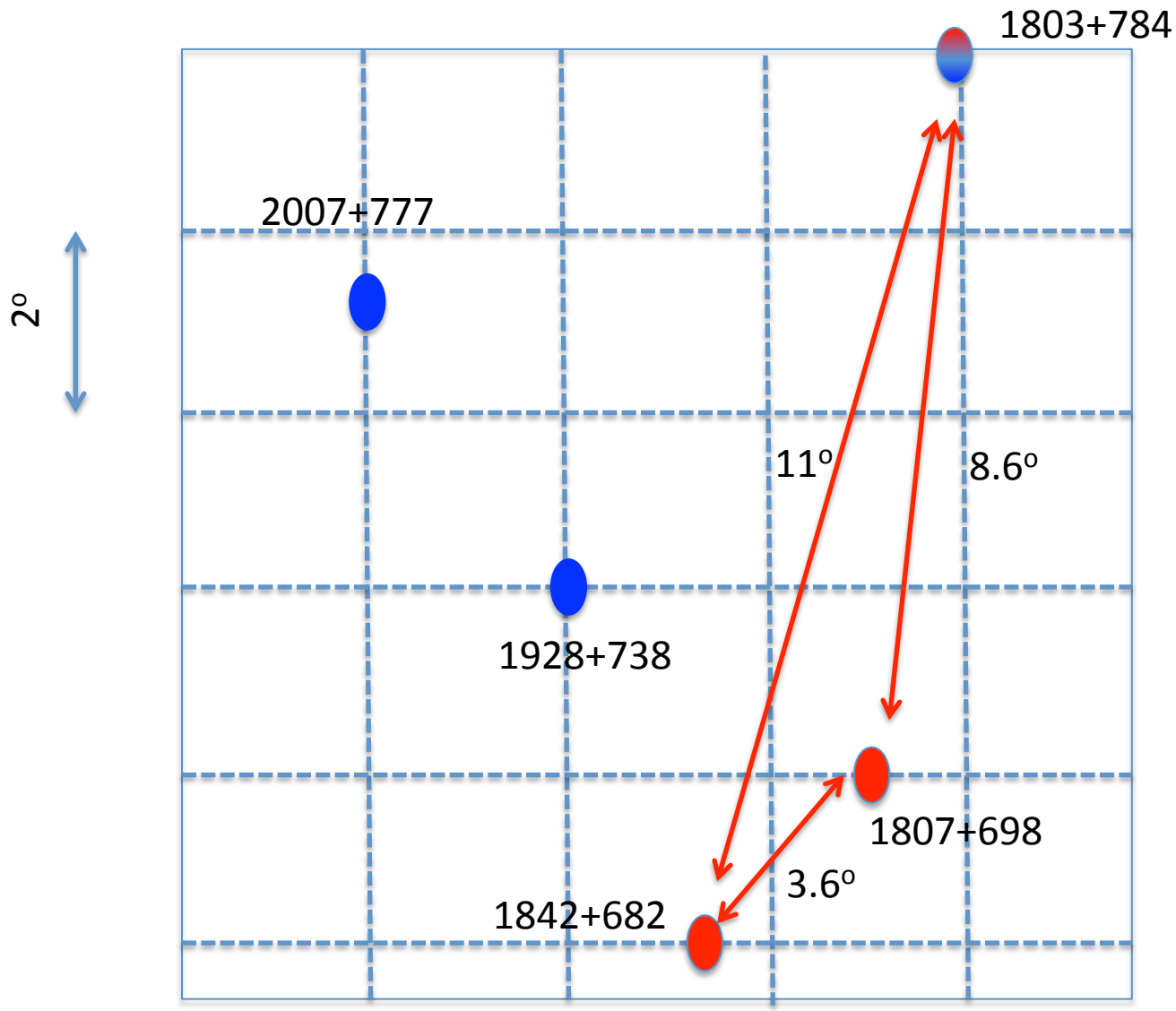
Demonstration: 4-band KVN SFPR observations of 5 AGNs



Triangle 1
Triangle 2

22,43,86,129 GHz

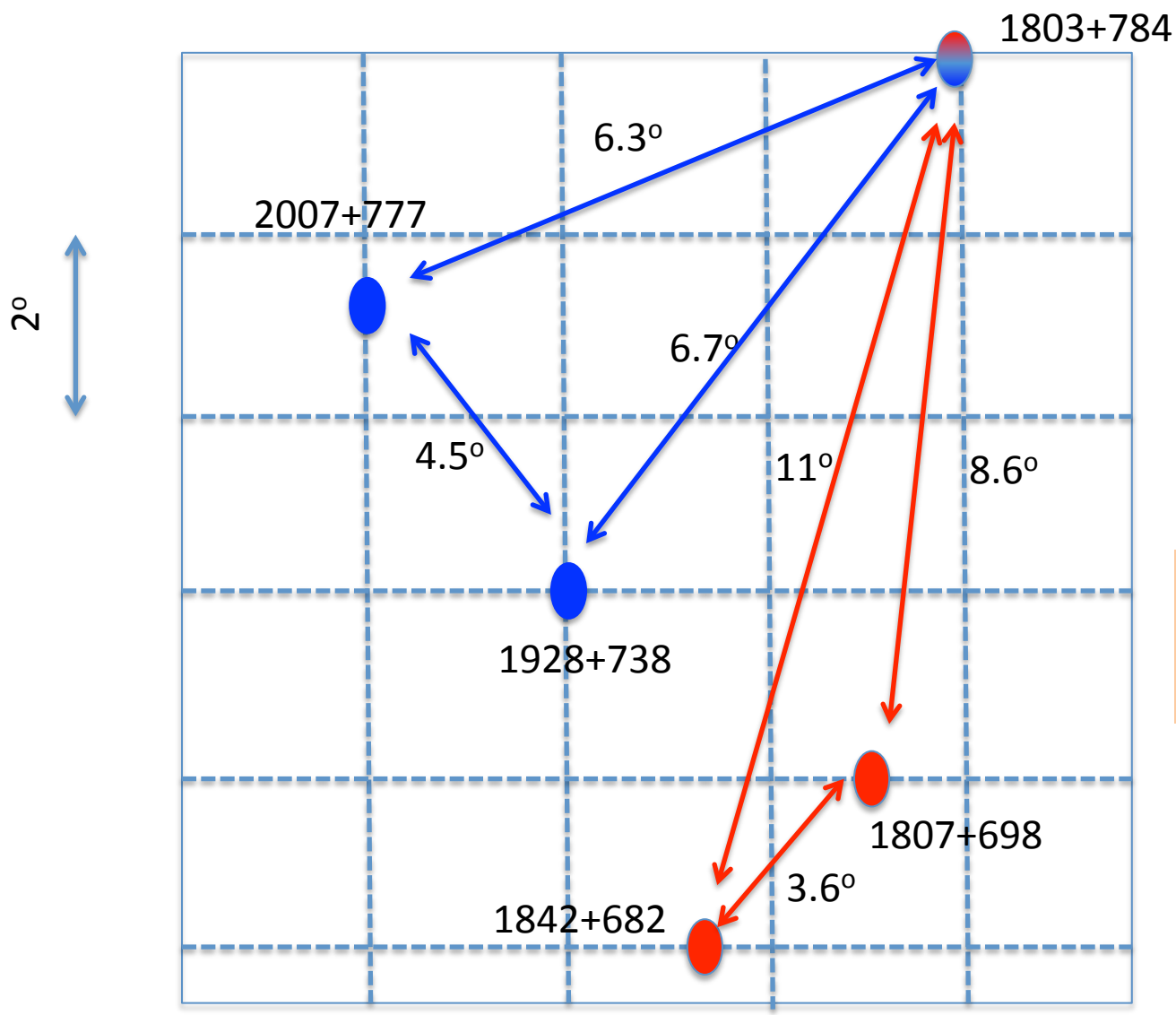
Demonstration: 4-band KVN SFPR observations of 5 AGNs



Triangle 1
Triangle 2

22,43,86,129 GHz

Demonstration: 4-band KVN SFPR observations of 5 AGNs

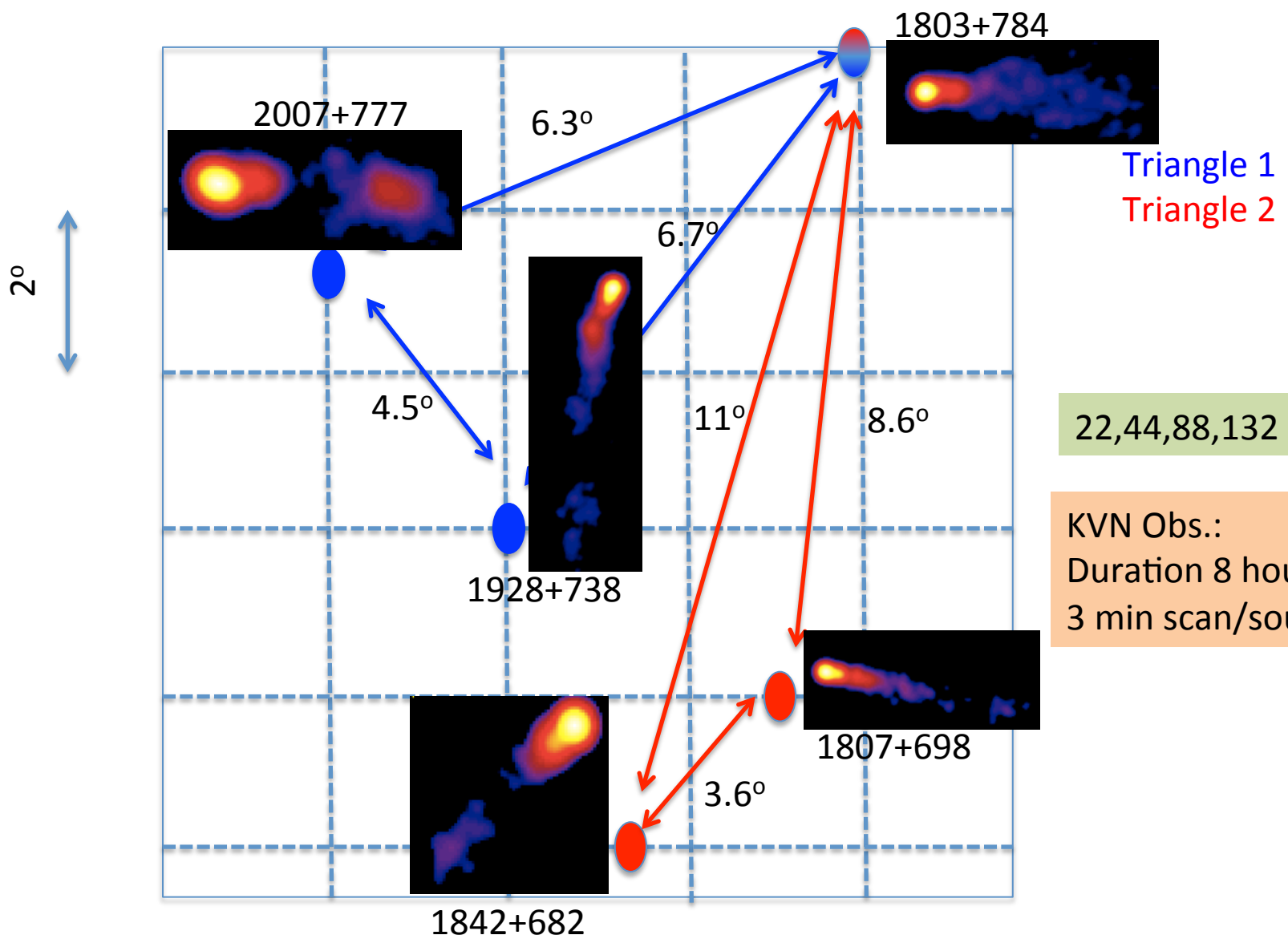


Triangle 1
Triangle 2

22,44,88,132 GHz

KVN Obs.:
Duration 8 hours
3 min scan/source

Demonstration: 4-band KVN SFPR observations of 5 AGNs



22,44,88,132 GHz

KVN Obs.:
Duration 8 hours
3 min scan/source

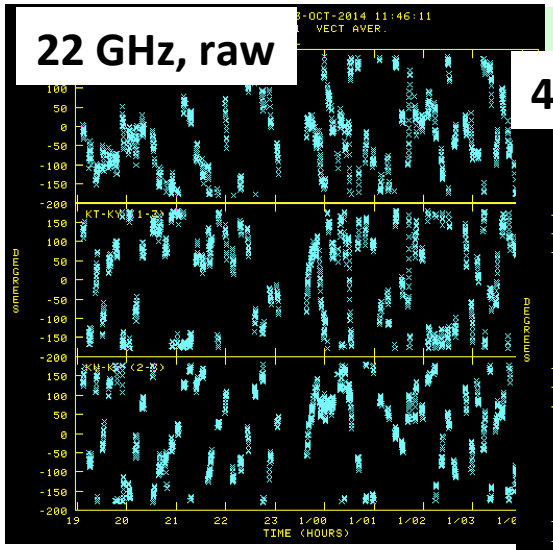
Demonstration: 4-band KVN SFPR observations of 5 AGNs

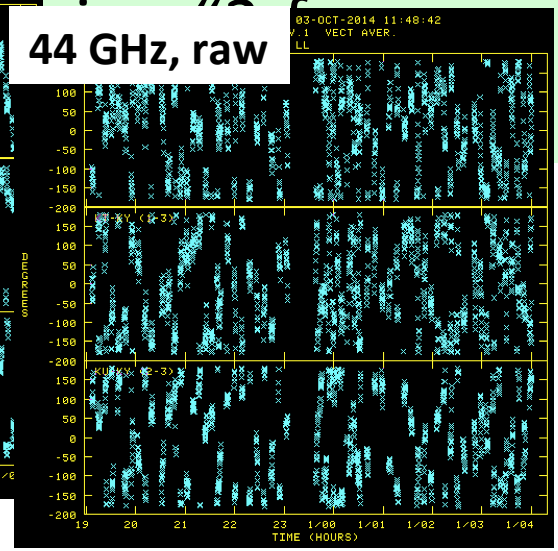
(1) Outcomes: Effective Tropospheric Compensation

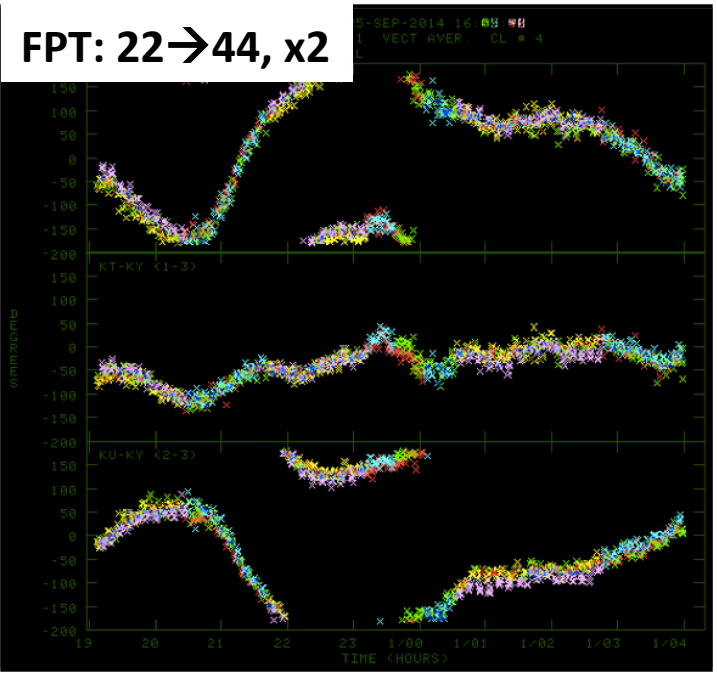
FPT analysis – "2-frequencies"

ies”

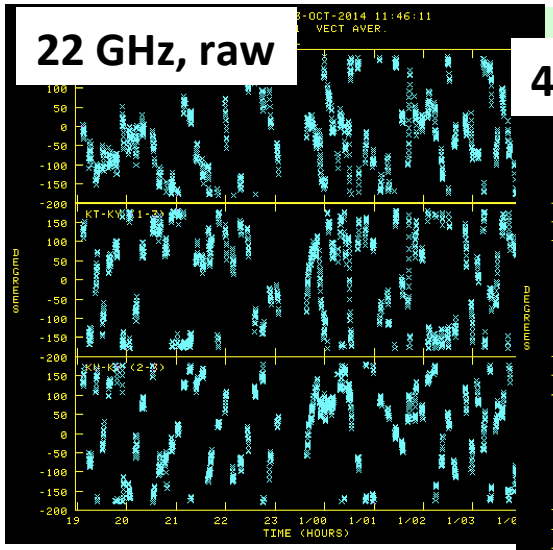
for a given ν_{low} (22GHz)



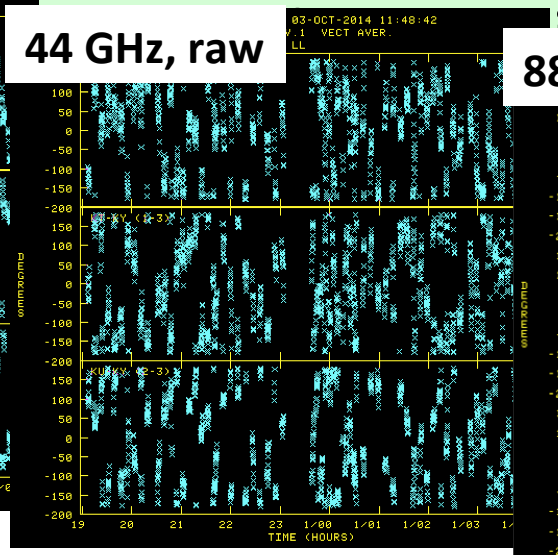




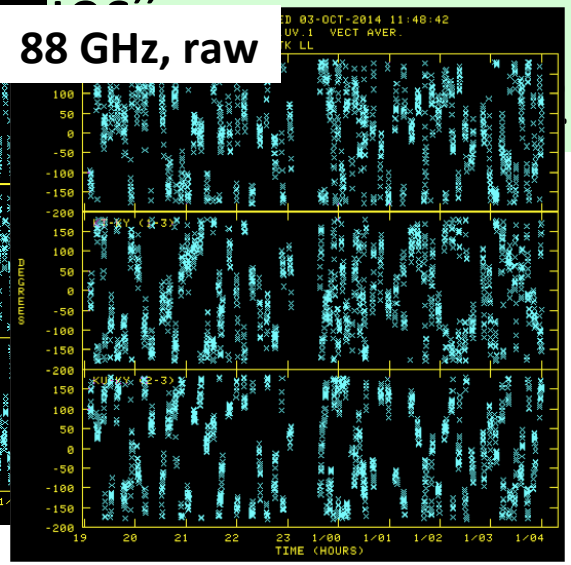
22 GHz, raw



44 GHz, raw

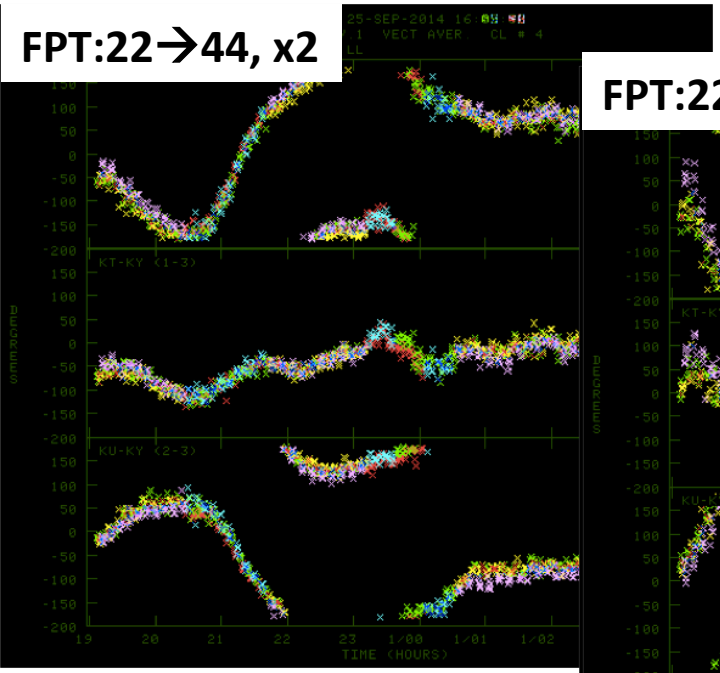


88 GHz, raw

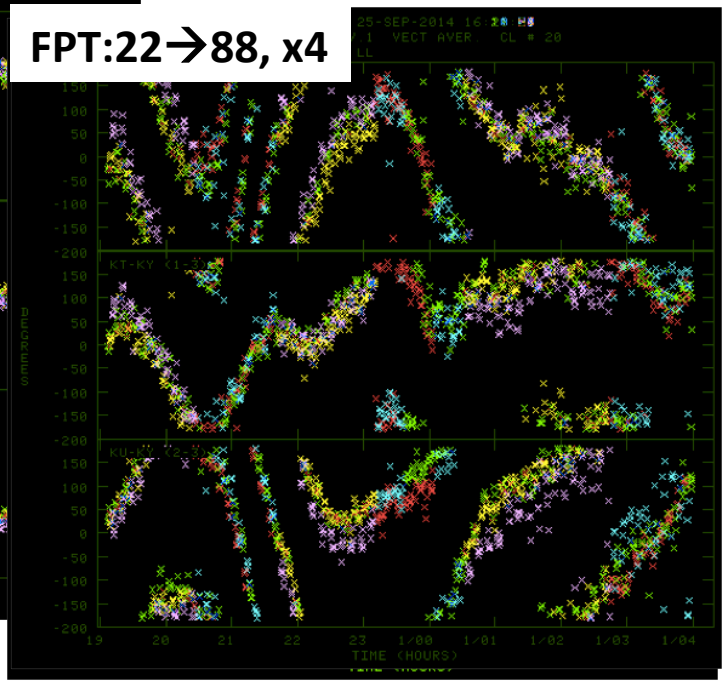


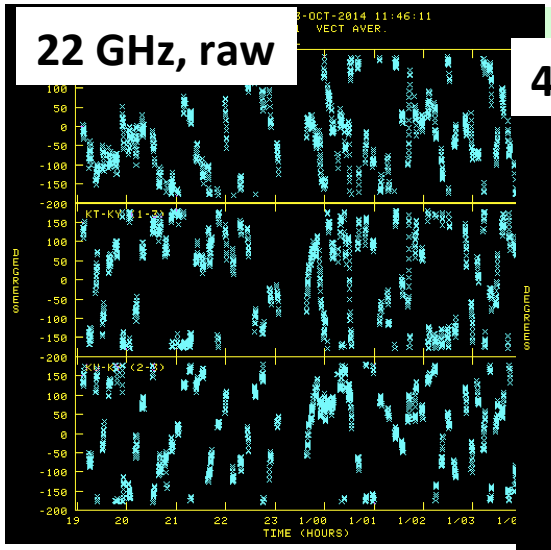
2GHz)

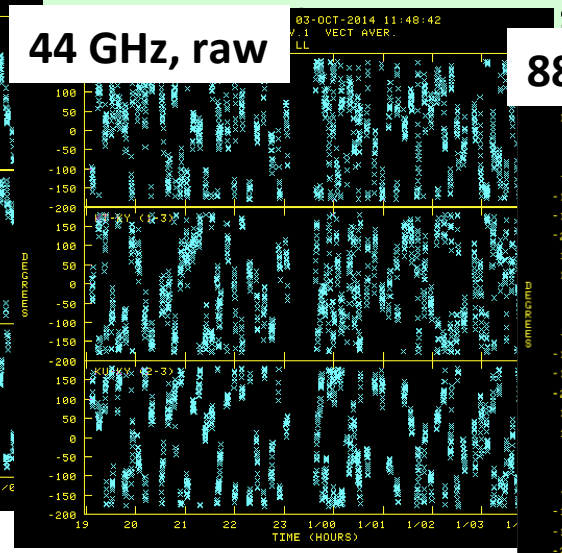
FPT:22→44, x2

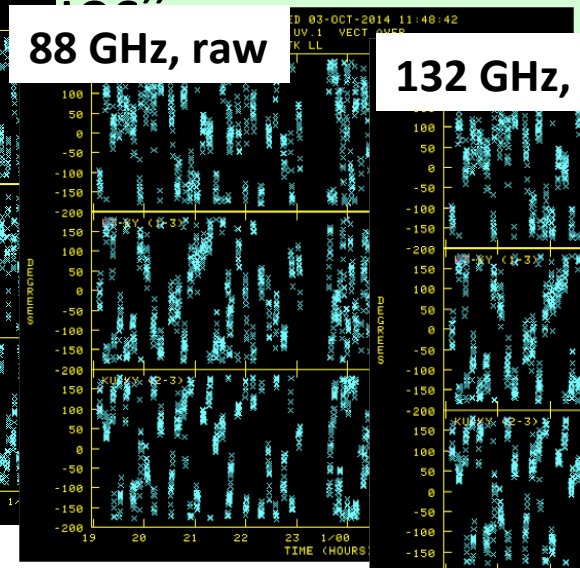


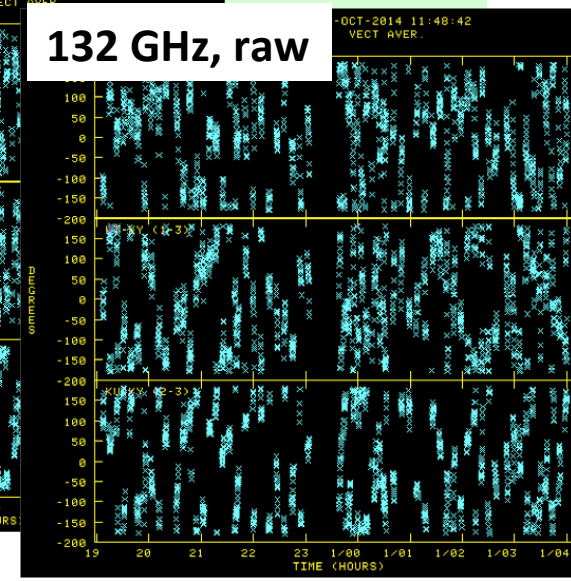
FPT:22→88, x4

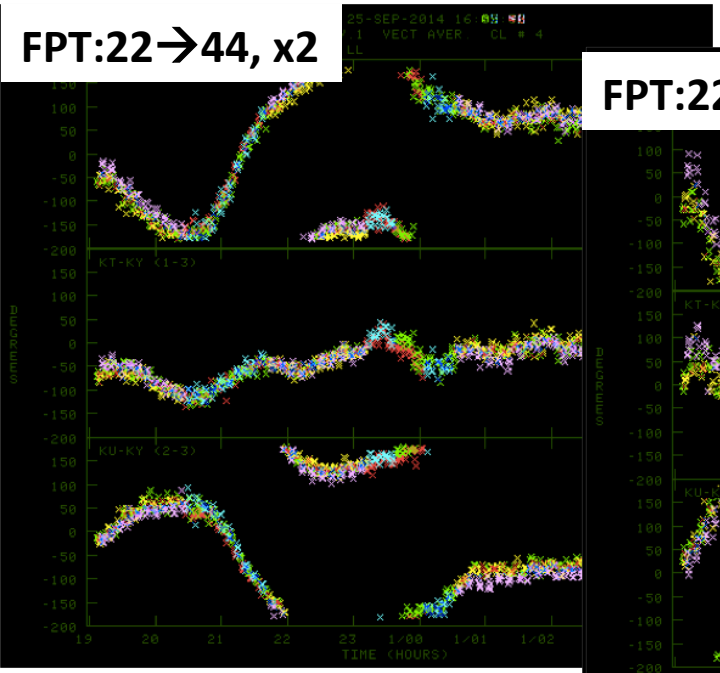


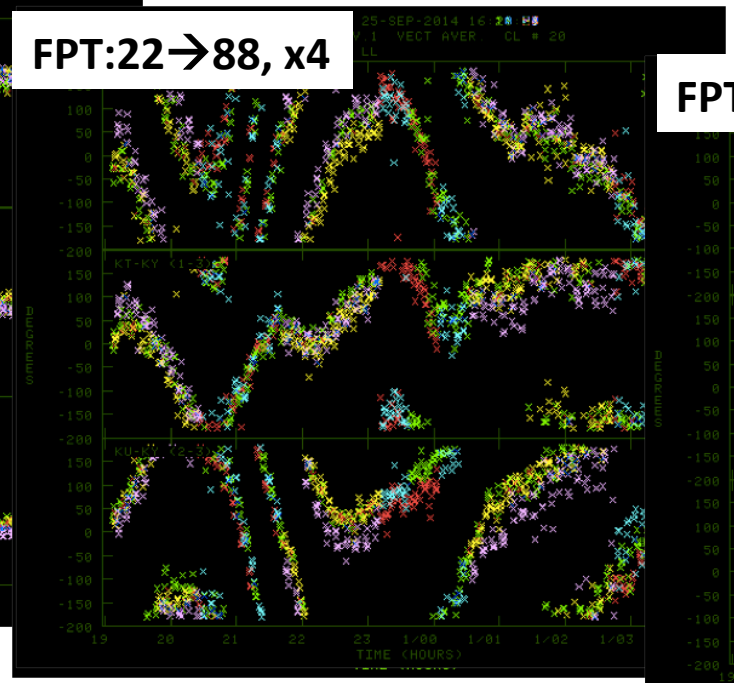

22 GHz, raw
TIME (HOURS)

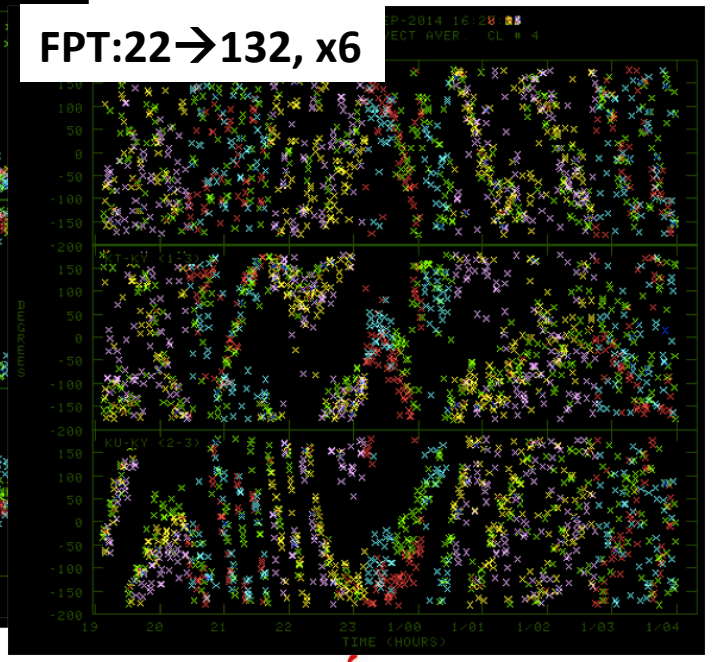

44 GHz, raw
TIME (HOURS)


88 GHz, raw
TIME (HOURS)


132 GHz, raw
TIME (HOURS)

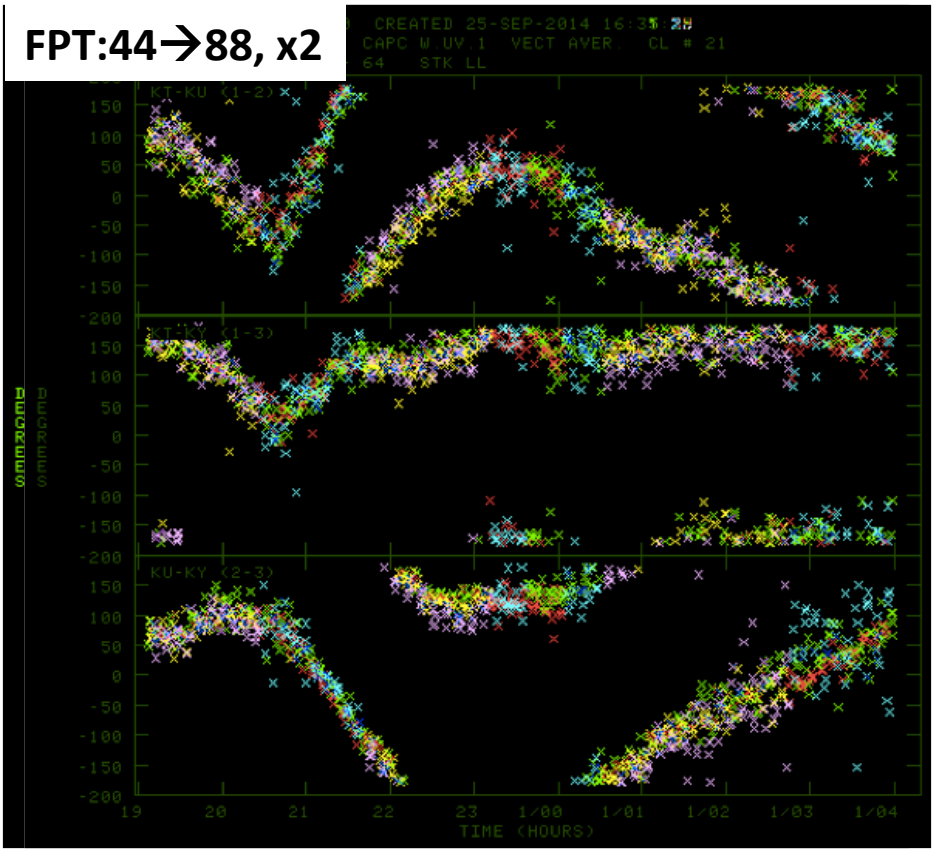

FPT:22→44, x2
TIME (HOURS)


FPT:22→88, x4
TIME (HOURS)

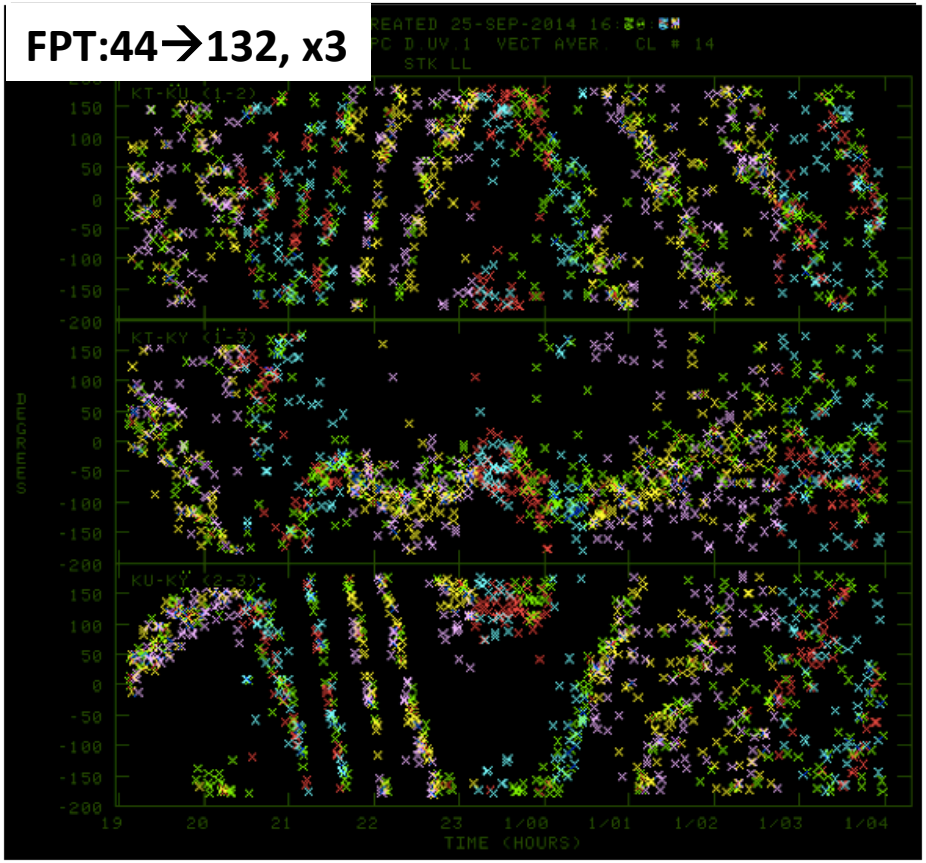

FPT:22→132, x6
TIME (HOURS)

FPT analysis – "2-frequencies"
Residuals increase with R, for a given ν_{low} (44 GHz)

FPT:44→88, x2

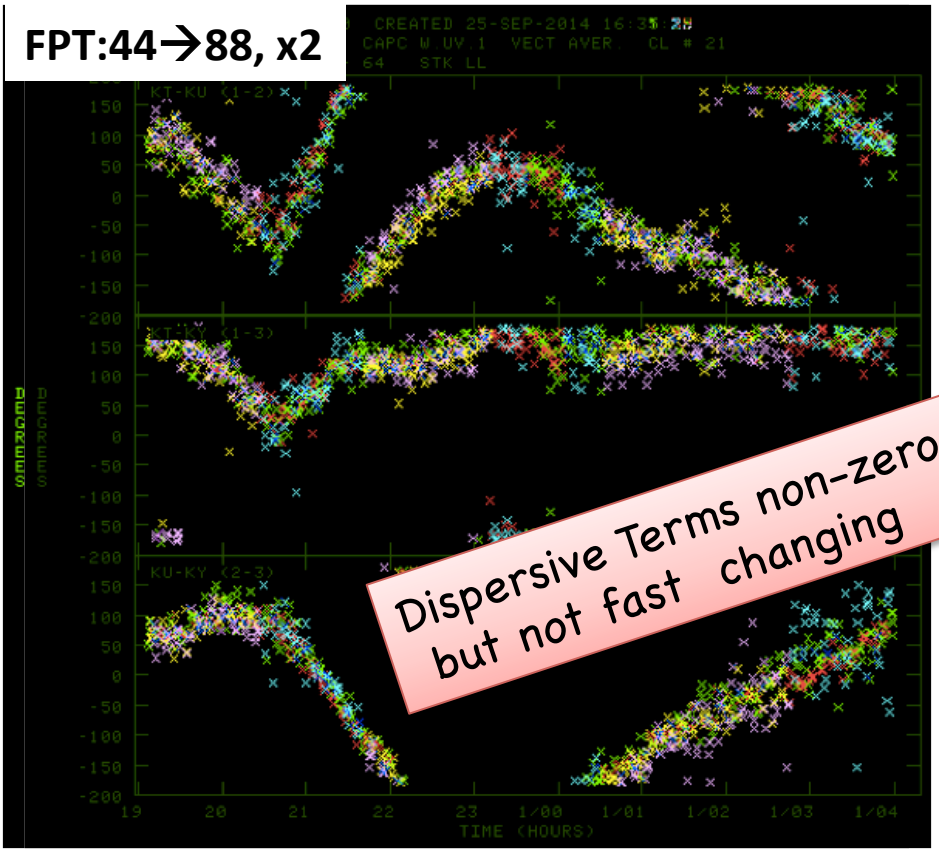


FPT:44→132, x3

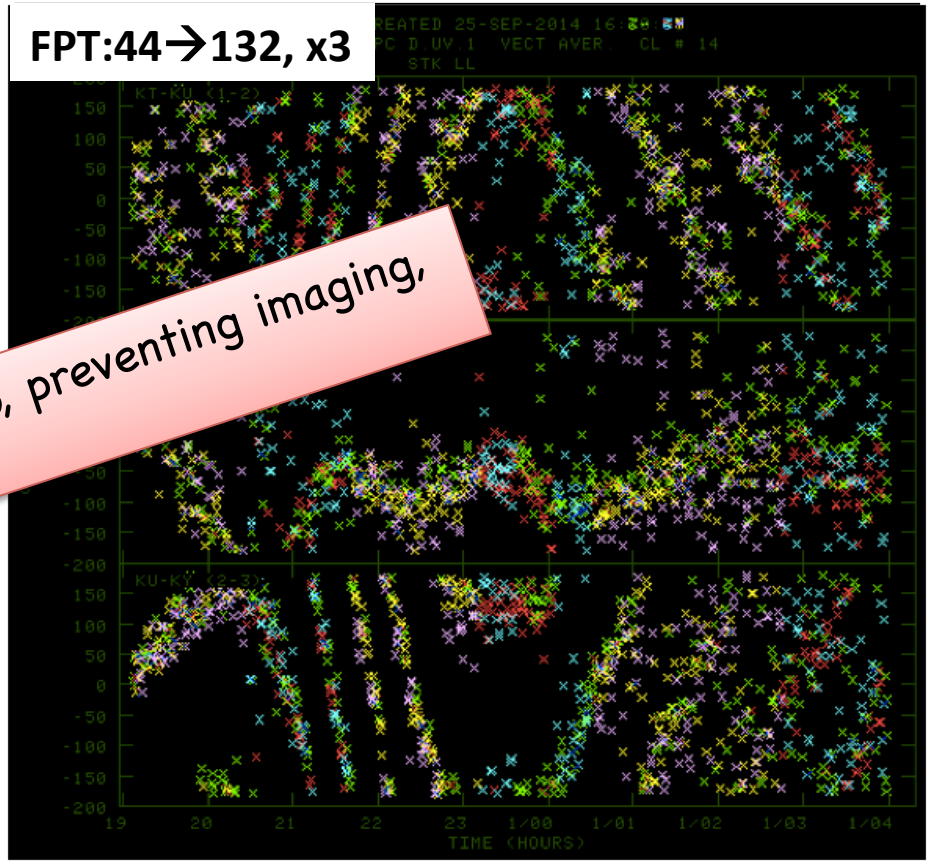


FPT analysis – "2-frequencies"
Residuals increase with R, for a given ν_{low} (44 GHz)

FPT:44→88, x2



FPT:44→132, x3



Dispersive Terms non-zero, preventing imaging, but not fast changing

$$R = \nu / \nu$$

Fast Slow Slow

$$\phi_A^{FPT} = \phi_{GEO} + \phi_{TRO} \quad \phi_{ION} + \phi_{INST} + \phi'_{A,STR} + 2\pi n_A$$

$$R*\phi_A = R*(\phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A)$$

Demonstration: 4-band KVN SFPR observations of 5 AGNs

(1) Outcomes: Effective Troposheric Compensation

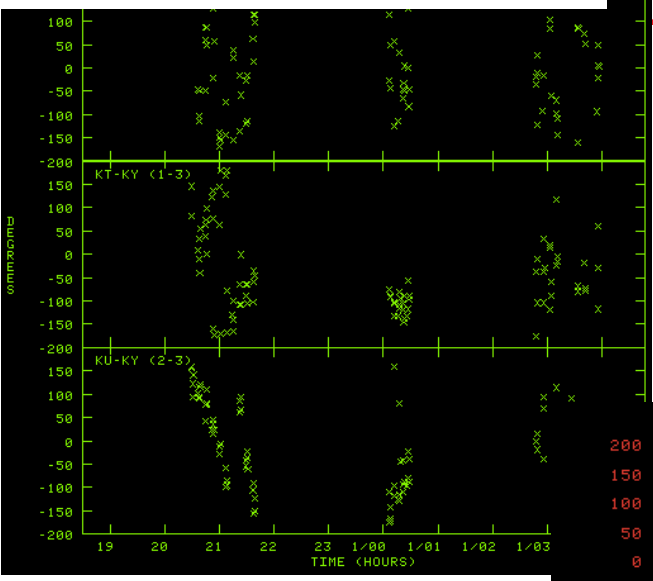
FPT analysis – "2-frequencies"

(2) Outcomes: Astrometry

SFPR analysis – "2-frequencies" & "2 sources"

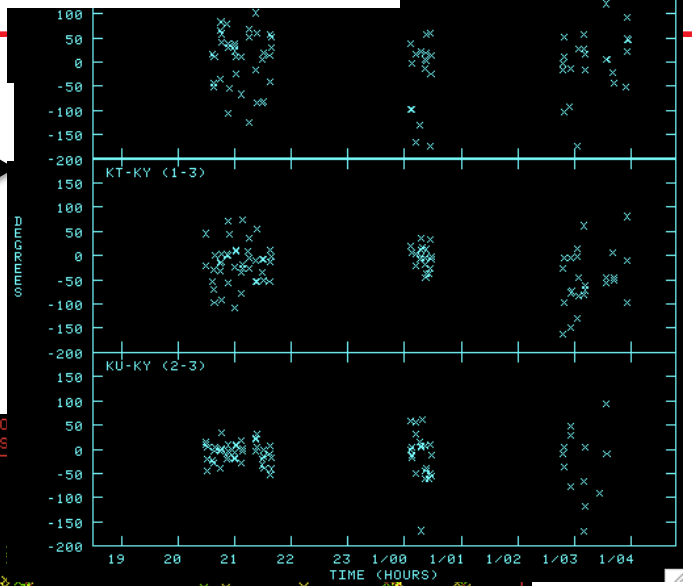
SFPR analysis – 132 GHz with 43GHz: 2007+777 (ref. 6.3° away)

A) 2007+777, FPT, 44→132, x3

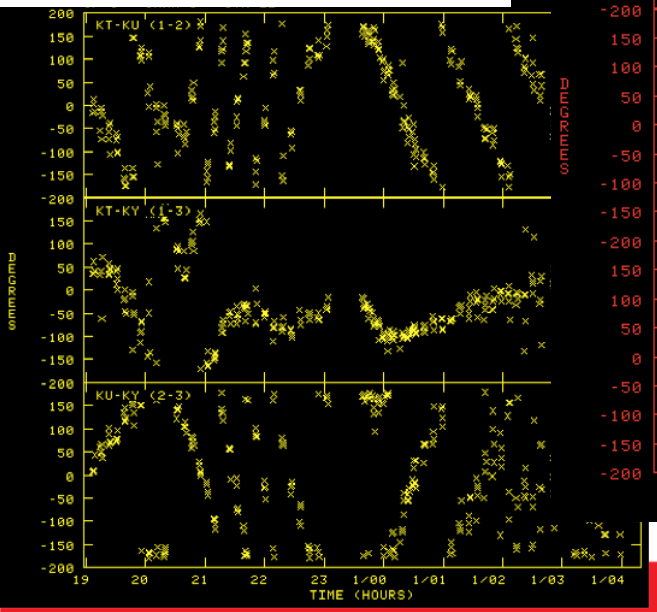


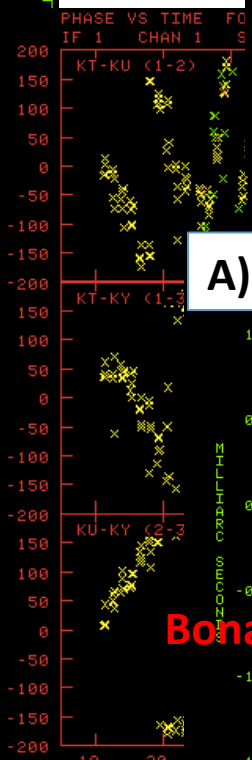
A) – B)

A) SFPR, 132 GHz



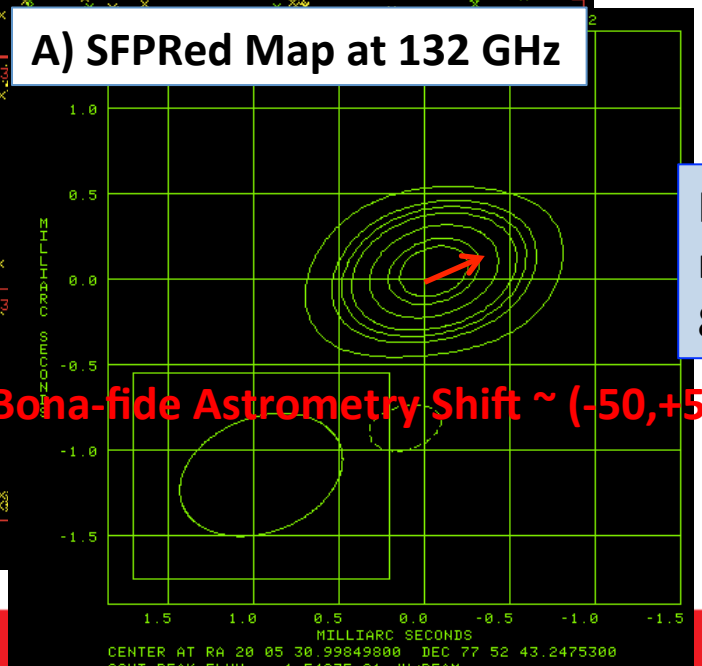
B) ref.,FPT, 44→132, x3





FFT

A) SFPRed Map at 132 GHz



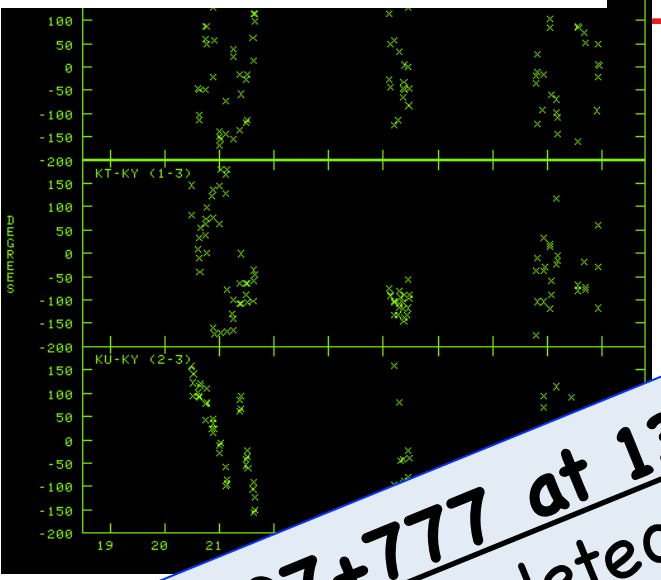
Peak Flux ~ 150 mJy
rms ~ 5mJy/beam
85-90% Flux Recovery

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

Korea Astronomy and Space Science Institute

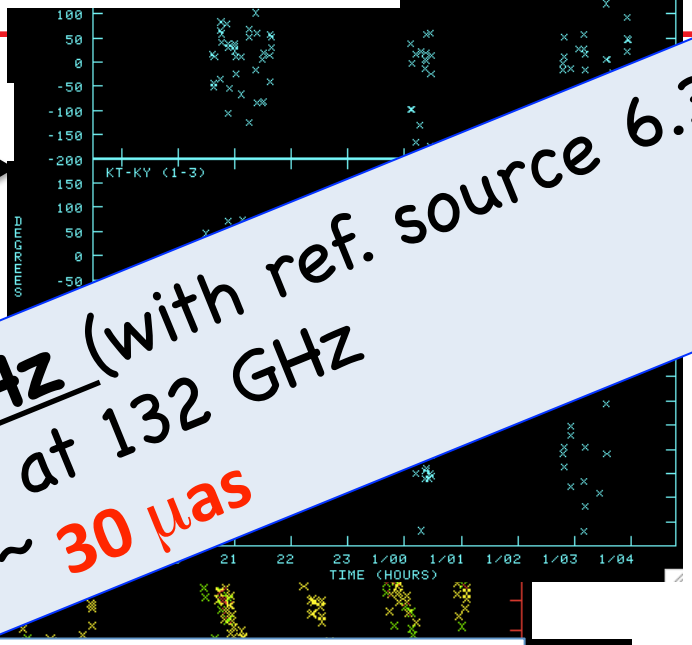
SFPR analysis – 132 GHz with 43GHz: 2007+777 (ref. 6.3° away)

A) 2007+777, FPT, 44→132, x3



A) – B)

A) SFPR, 132 GHz

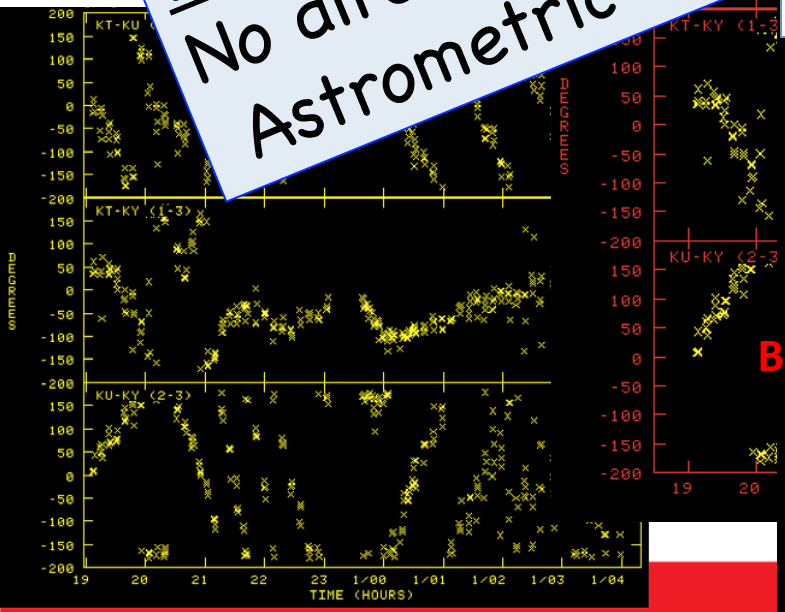


2007+777 at 132 GHz (with ref. source 6.3° away)

No direct detections at 132 GHz

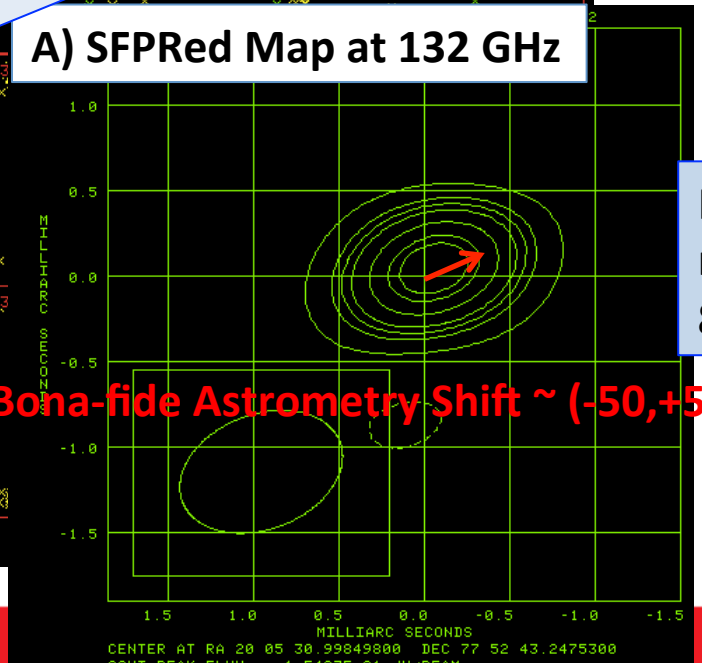
Astrometric Error ~ 30 μas

B) ref.



FFT

A) SFPRed Map at 132 GHz



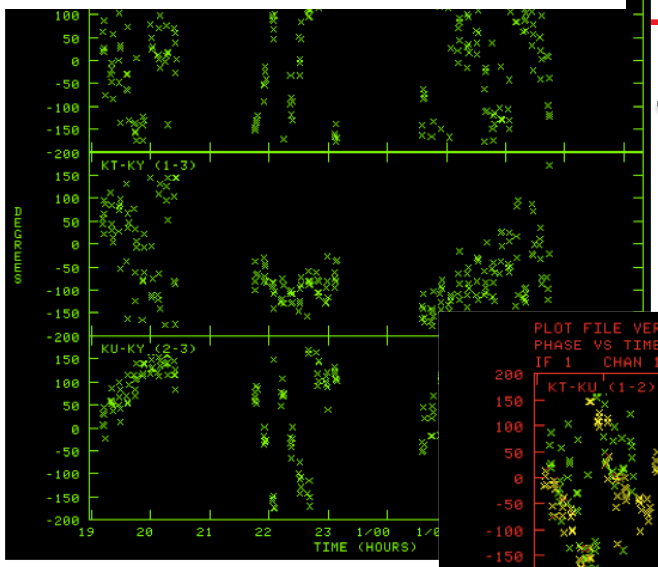
Peak Flux ~ 150 mJy
rms ~ 5mJy/beam
85-90% Flux Recovery

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

Korea Astronomy and Space Science Institute

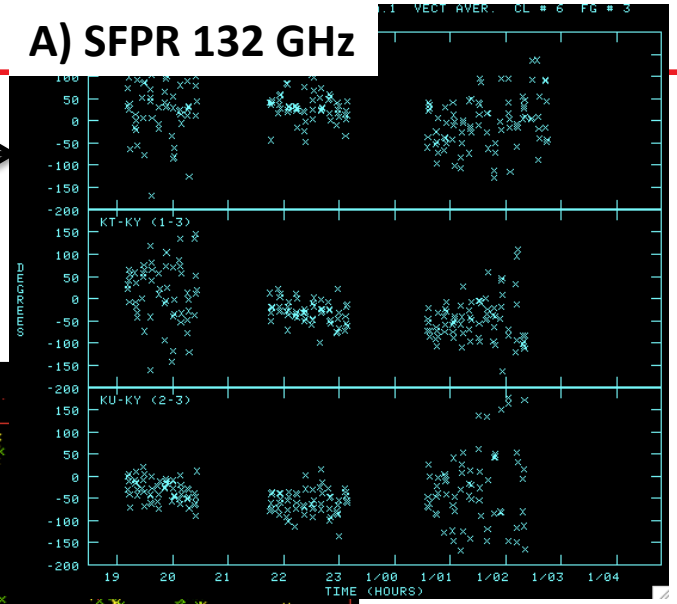
SFPR analysis – 132 GHz with 43GHz: 1842+681 (ref. 11° away)

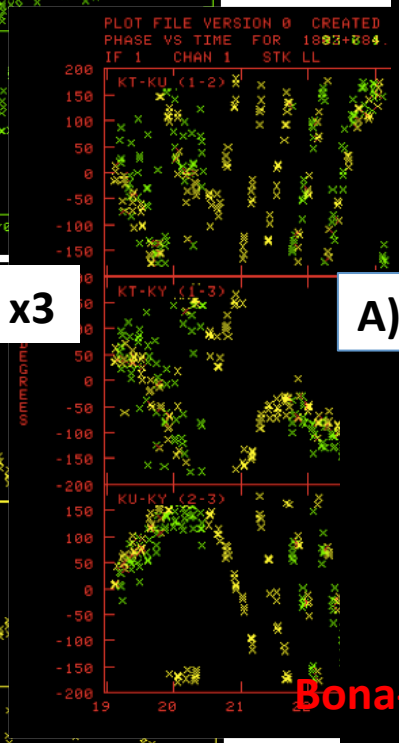
A) 1842+681 FPT,44→132, x3



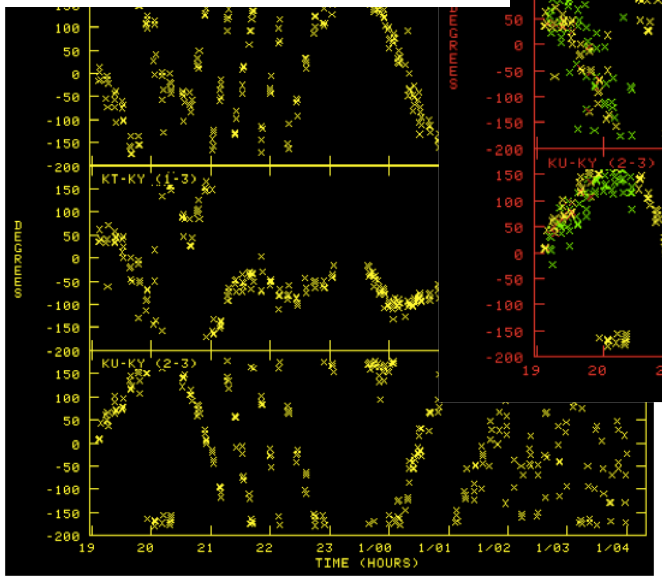
A) – B)

A) SFPR 132 GHz



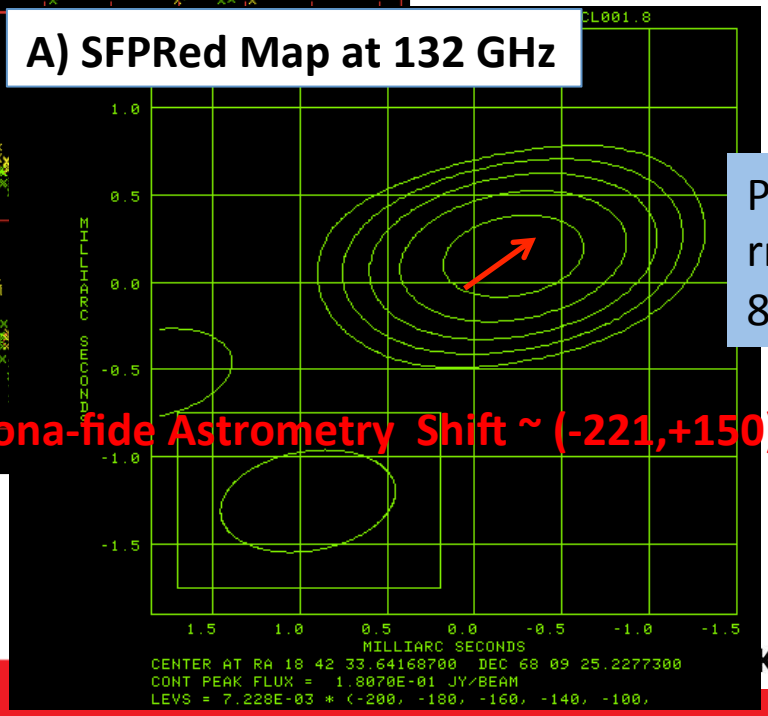


B) ref., FPT,44→132, x3



FFT

A) SFPRed Map at 132 GHz



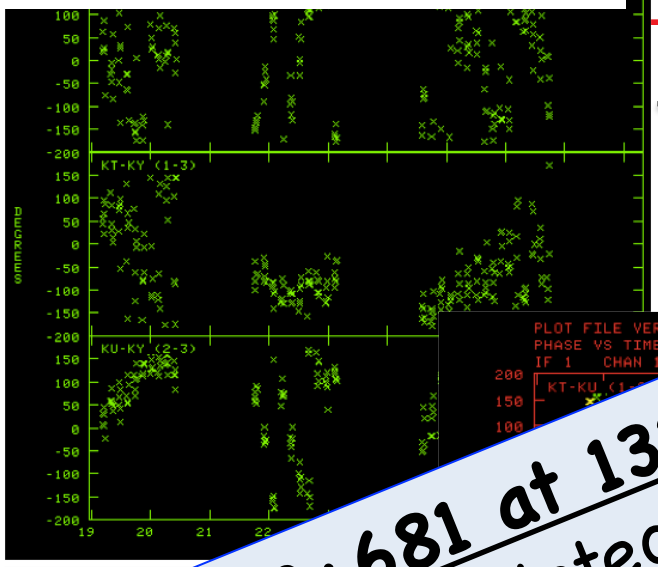
Peak Flux ~ 100 mJy
rms ~ 5 mJy/beam
87% Flux Recovery

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

Korea Astronomy and Space Science Institute

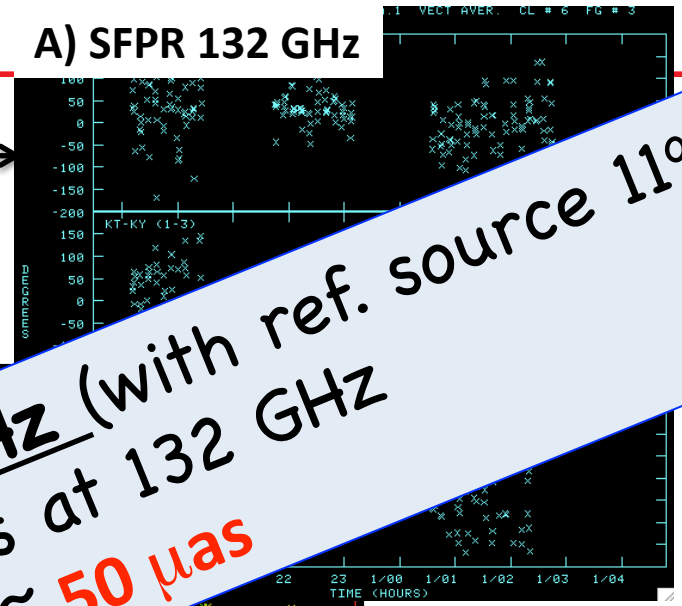
SFPR analysis – 132 GHz with 43GHz: 1842+681 (ref. 11° away)

A) 1842+681 FPT,44→132, x3



A) – B)

A) SFPR 132 GHz



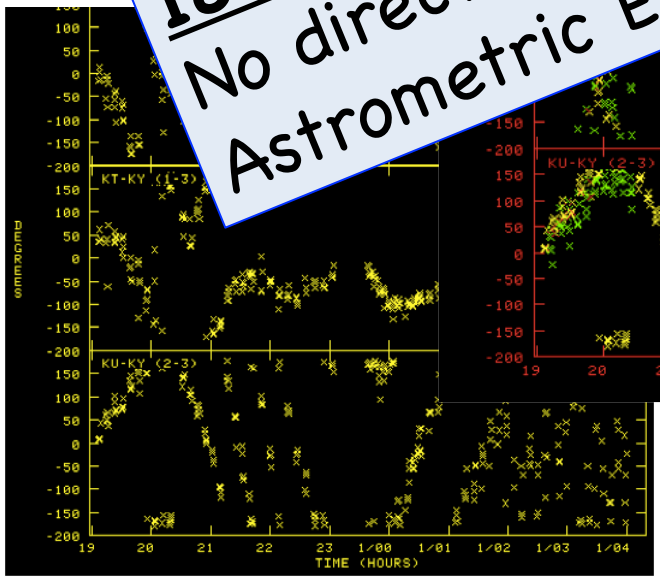
1842+681 at 132 GHz (with ref. source 11° away)

No direct detections at 132 GHz

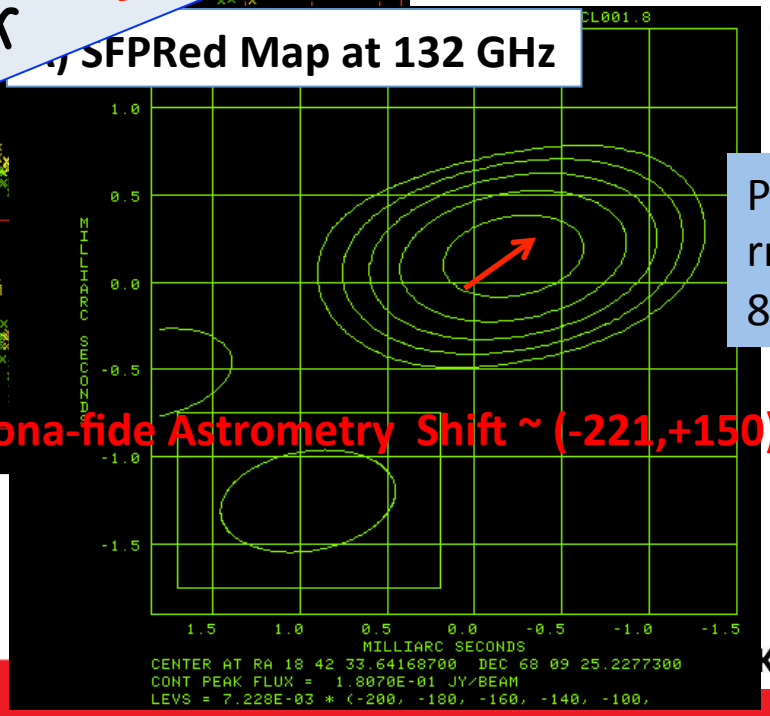
Astrometric Error ~ 50 μas

FFT

B) ref



) SFPRed Map at 132 GHz



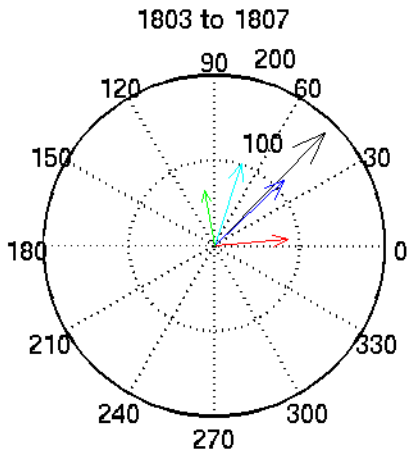
Peak Flux ~ 100 mJy
rms ~ 5 mJy/beam
87% Flux Recovery

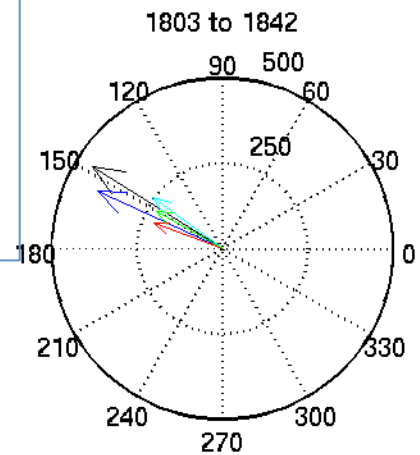
Bona-fide Astrometry Shift ~ (-221,+150) μas

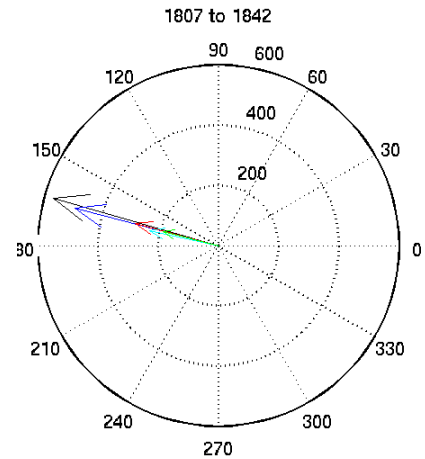
Korea Astronomy and Space Science Institute

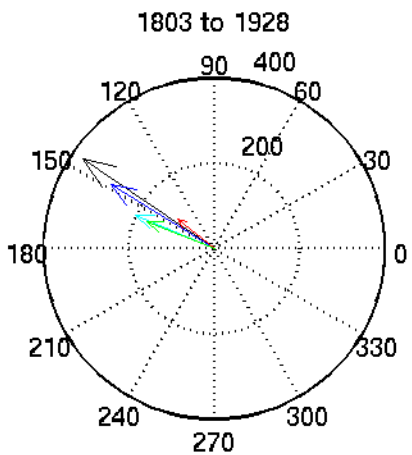
SFPR Astrometric RELATIVE Measurements: between TWO frequencies & TWO sources

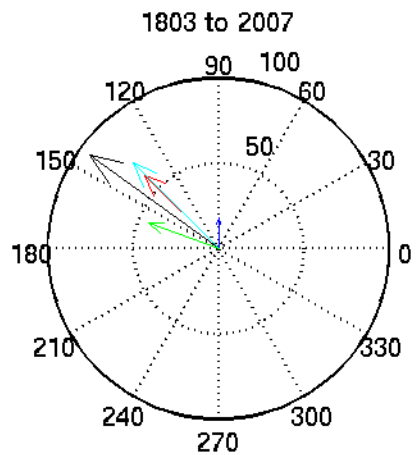
Red-KQ
Blue KW
Black KD
Green QW
Cyan QD

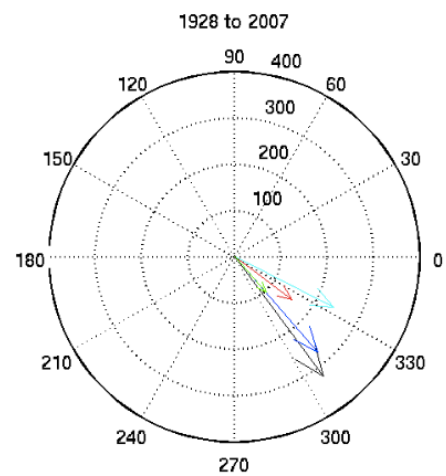












Demonstration: 4-band KVN SFPR observations of 5 AGNs

(1) Outcomes: Effective Tropospheric Compensation

FPT analysis – "2-frequencies"

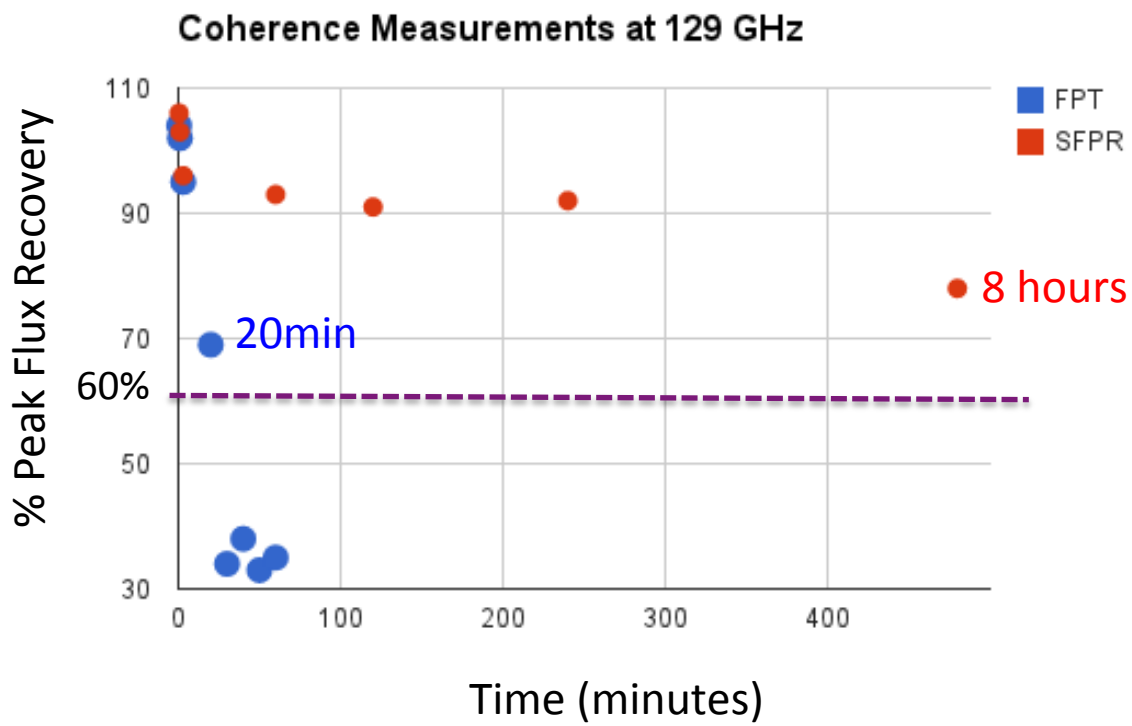
(2) Outcomes: Astrometry

SFPR analysis – "2-frequencies" & "2 sources"

(3) Outcomes: Increased Coherence Time

FPT & SFPR analysis

Demonstration: Coherence Studies



Freq.Pair	Analysis	Effective Coherence Time
44→ 132 GHz	FPT (or MFPR)	20 min
44→ 132 GHz	SFPR (*11deg)	> 8 hours

➔ NEW: From Relative to Individual Source Shifts: Single Value Decomposition Method

$\nu_{low} \rightarrow \nu_{high}$

θ Position shift

1,2,3,4,5 sources

$$[A\text{-}B] = [M] \times [S]$$

SVD

$[S]$ Degenerate Solution

$$\begin{bmatrix} \theta_{12} \\ \theta_{13} \\ \theta_{23} \\ \theta_{14} \\ \theta_{15} \\ \theta_{45} \end{bmatrix}$$

Astrometric Relative Measurements

$$\begin{bmatrix} 1 & -1 & 0 & \ldots\ldots \\ 1 & 0 & -1 & \ldots\ldots \\ 0 & 1 & -1 & \ldots. \\ . & \ldots\ldots & & \\ . & & \ldots\ldots. & \\ . & \ldots\ldots\ldots\ldots\ldots & & \end{bmatrix}$$

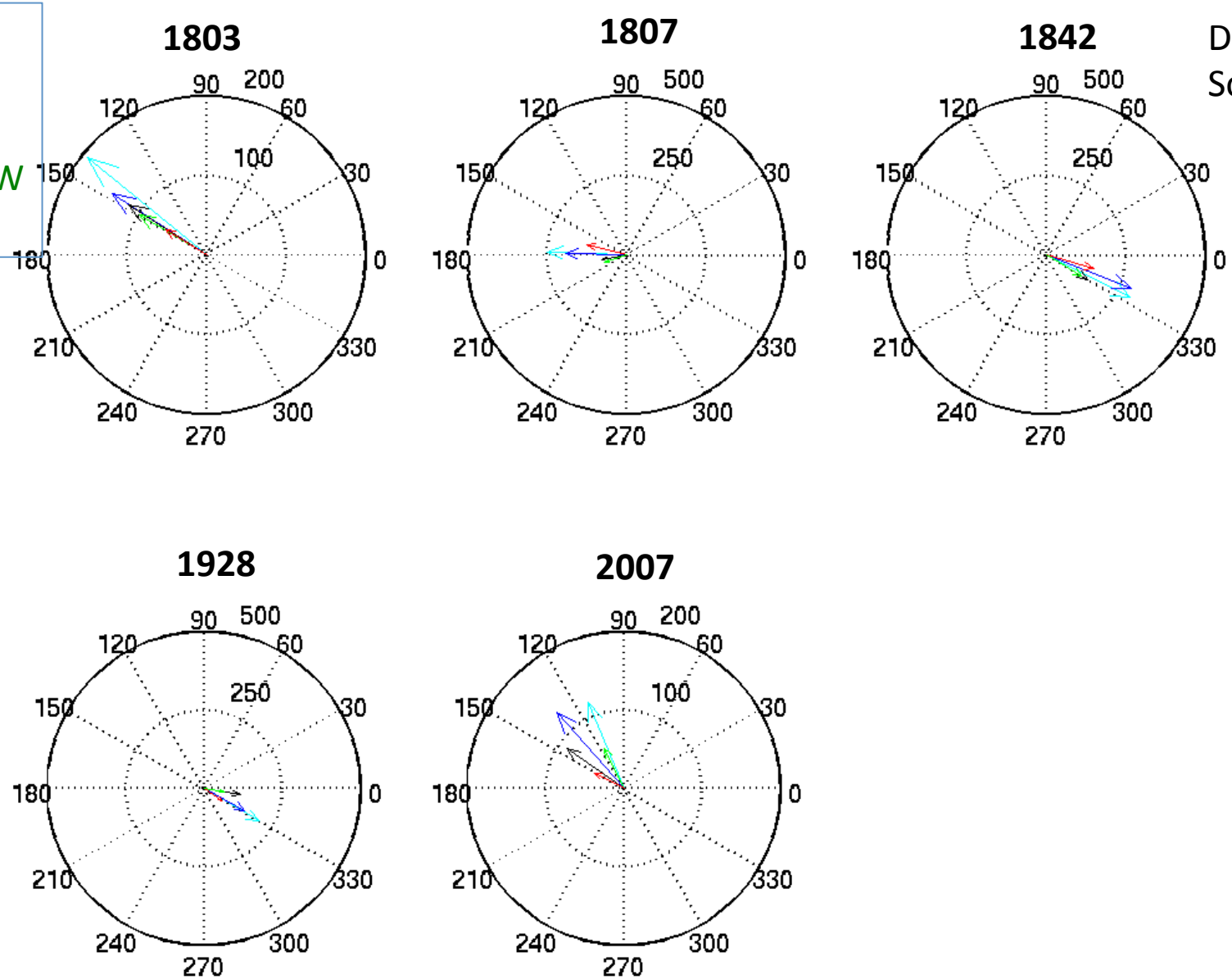
Source Pair Matrix

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \end{bmatrix}$$

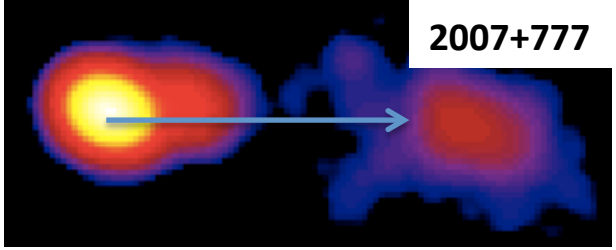
Individual Source Shifts

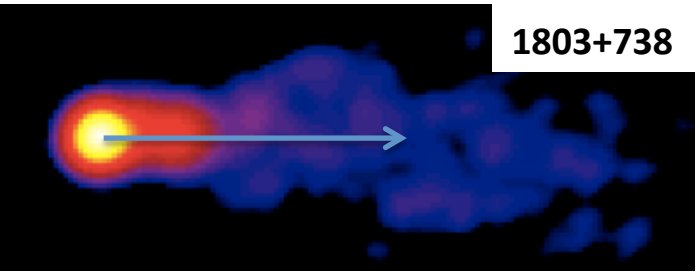
Individual Source Shifts: Single Value Decomposition Method

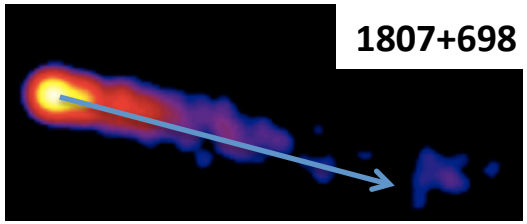
Red KQ
Blue KW
Cyan KD
Green QW
Black QD



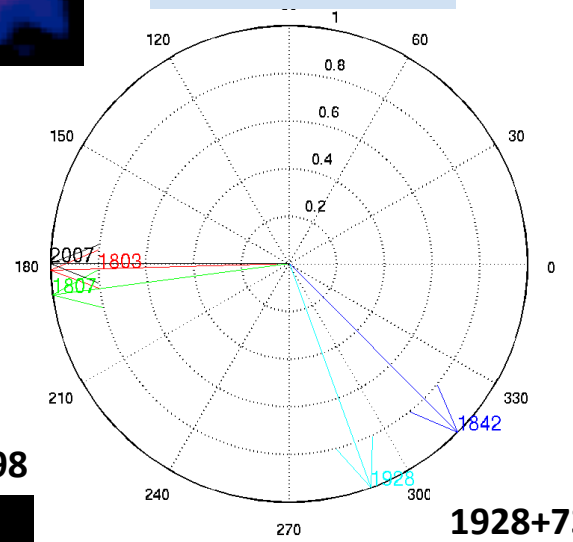
Degenerate Solution

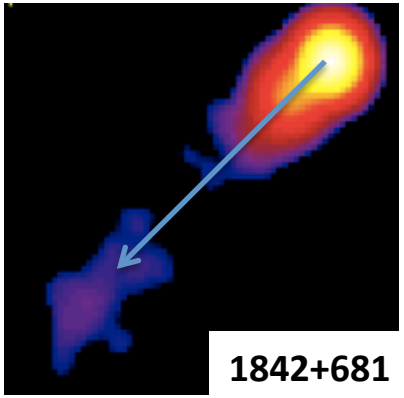


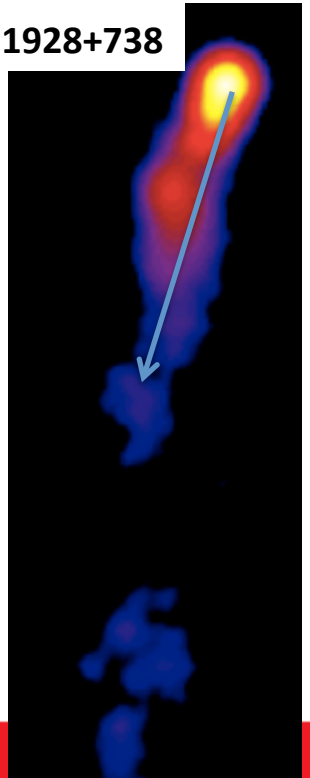




Jet Directions







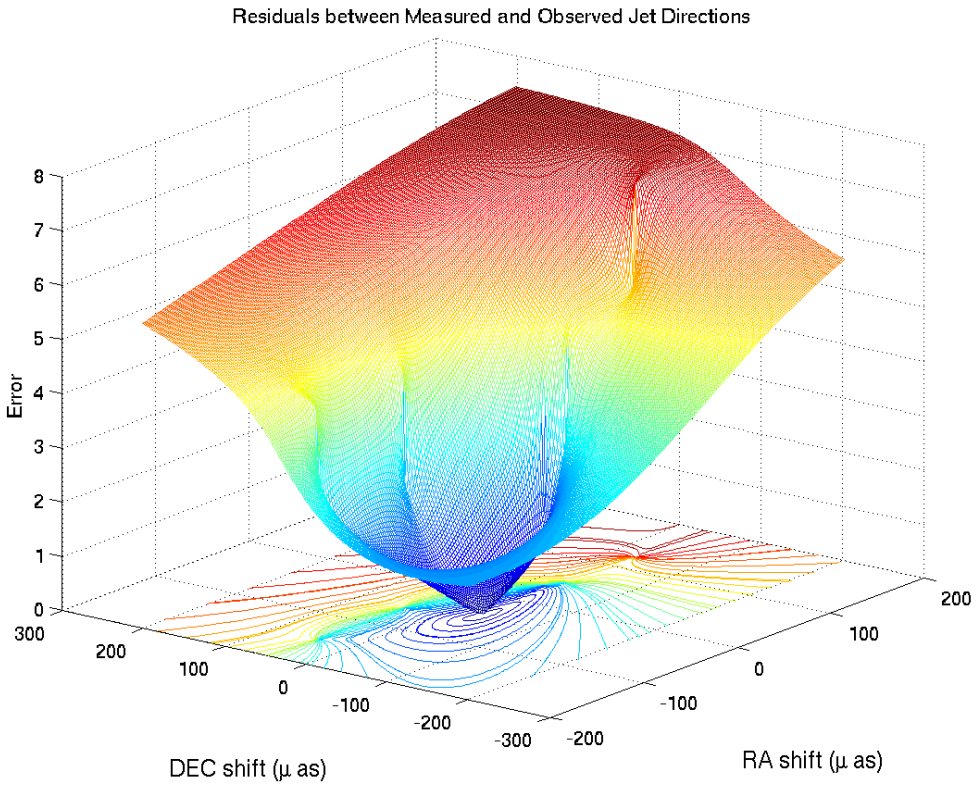
In the maps:

RA

In the plots:

RA

Constraint: Jet Directions



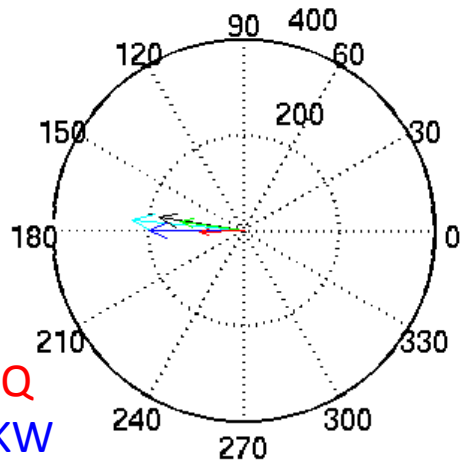
- Independent analysis per frequency pair
- PLOT: Unique common shift (x=RA,y=DEC) for all 5 sources, and combined (all-source Misalignment with corresponding Jet Directions (z=Error).
- More sources and wider distribution of PAs sets stronger constraints.

Individual Source Shifts: Single Value Decomposition Method PLUS Jet Direction Constraint

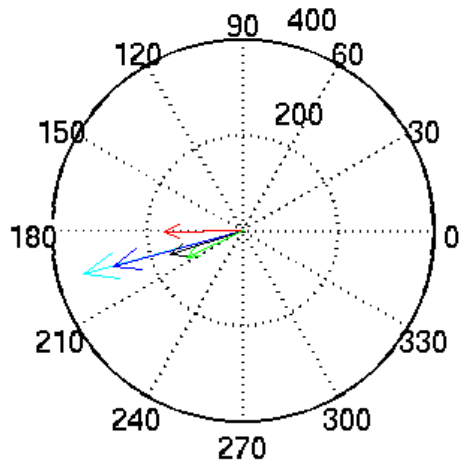
Non-Degenerate Solution

Red KQ
Blue KW
Cyan KD
Green QW
Black QD

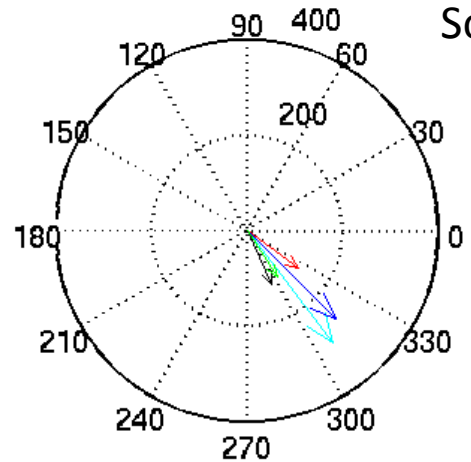
1803



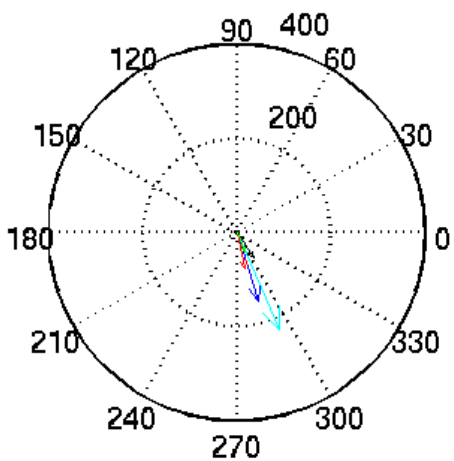
1807



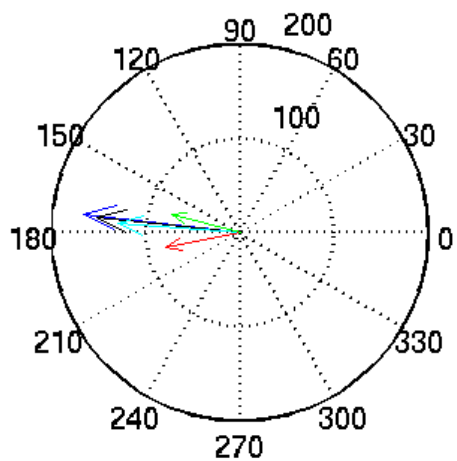
1842



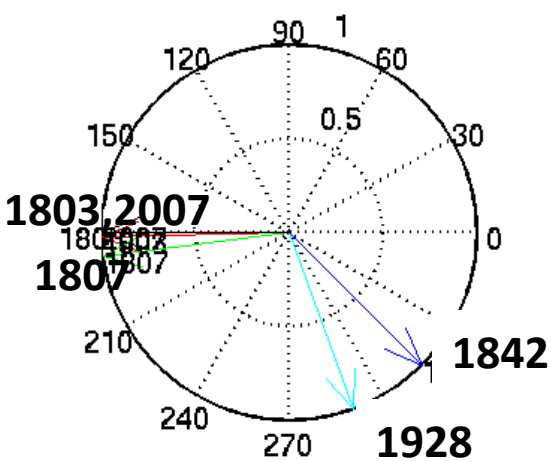
1928



2007



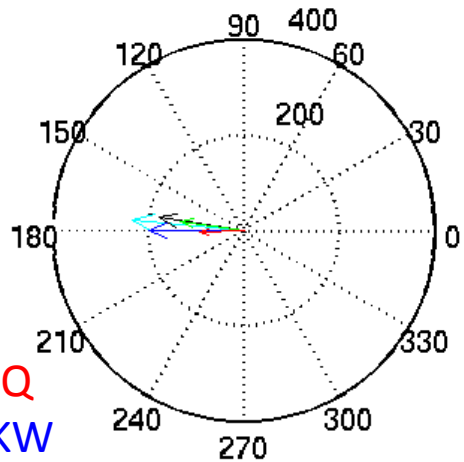
Jet Directions



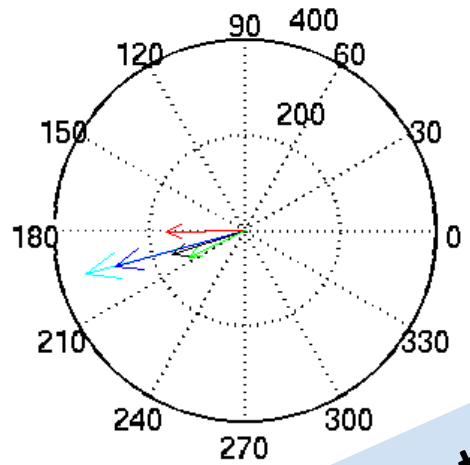
Individual Source Shifts: Single Value Decomposition Method PLUS Jet Direction Constraint

Non-Degenerate Solution

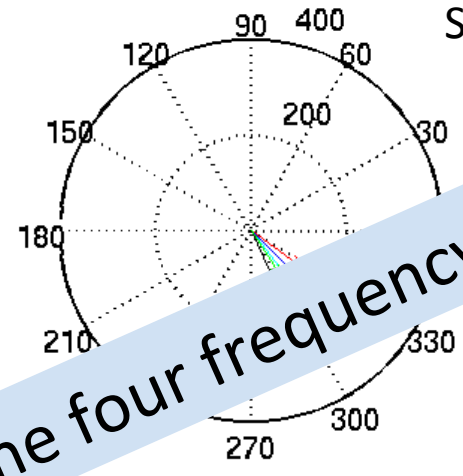
1803



1807



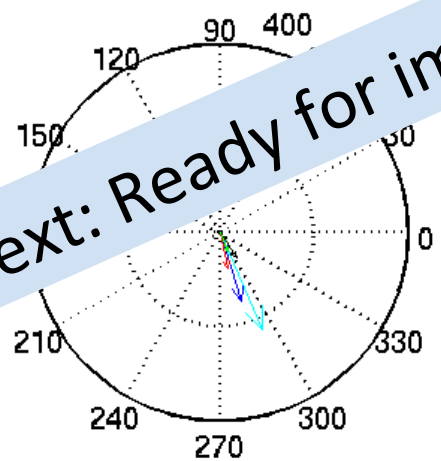
1842

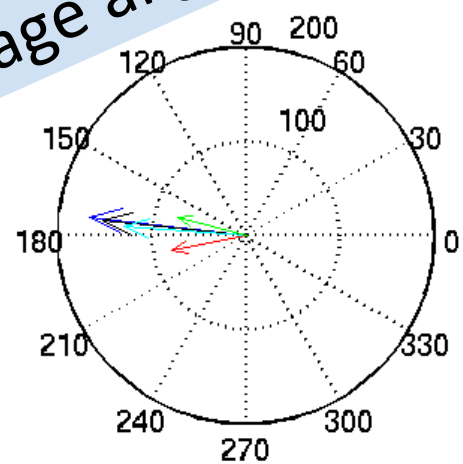


Red KQ
Blue KW
Cyan KD
Green QW
Black QD

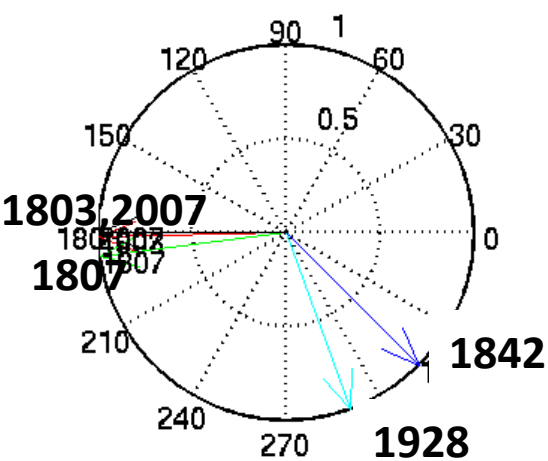
Next: Ready for image alignment at the four frequency bands

1928





Jet Directions



Astrophysical Applications

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.

Summary

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.