ICRAR

International Centre for Radio Astronomy Research

Methods for mm-VLBI using Multi-Frequency Observations

Maria J. Rioja
ICRAR (Australia), OAN (Spain)

Richard Dodson
ICRAR (Australia)

Curtin University

The Government of Western Australia

The University of Western Australia

Overview

- Context
- A mm-VLBI method: SOURCE FREQUENCY PHASE REFERENCING (SFPR)

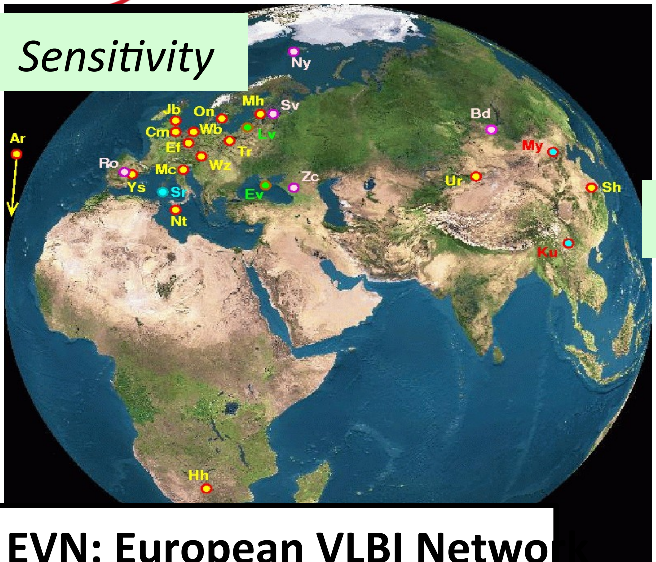
  → Outcomes: 1) Effective Atmospheric Compensation,

  2) Increased Sensitivity, and

  3) Astrometry
- Empirical Demonstration with multi-frequency observations with the Korean VLBI Network, up to 132 GHz
- Work-in-progress and what's next?

VLBI NETWORKS

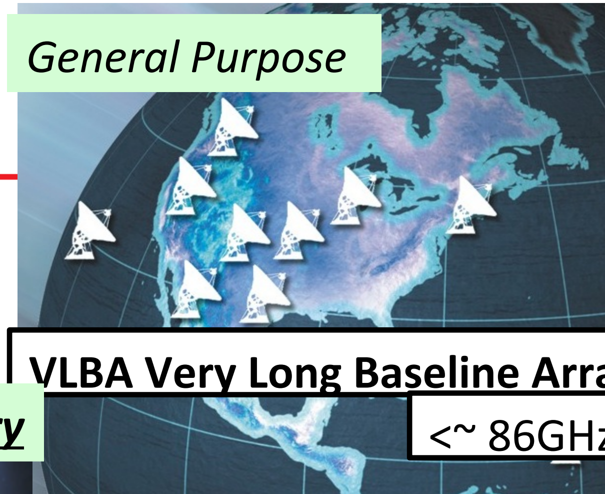
Sensitivity



EVN: European VLBI Network

<~ 22GHz

General Purpose



VLBA Very Long Baseline Array

<~ 86GHz

Highest Frequency Astrometry

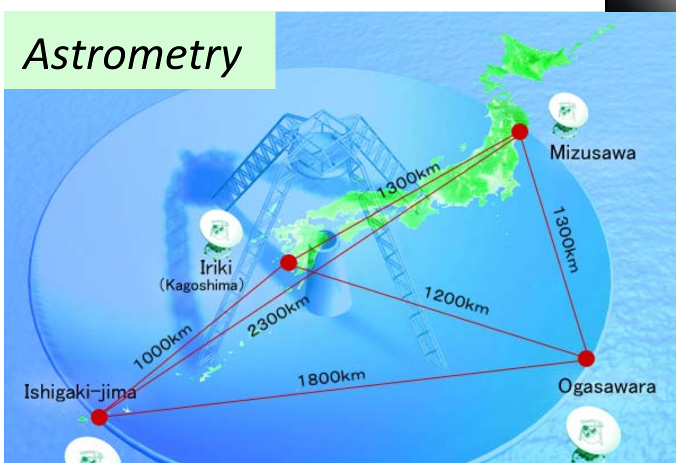
KVN Korean VLBI Network

22/43/86/129 GHz

GMVA Global mm VLBI Array

86GHz

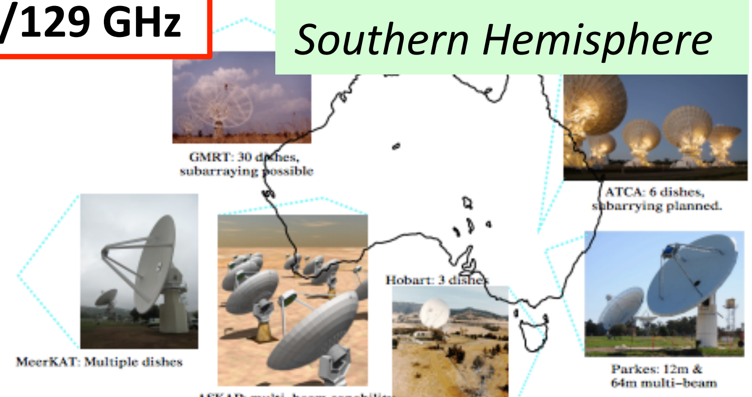
Astrometry



VERA VLBI for Earth Rotation and Astrometry

22/43 GHz

Southern Hemisphere



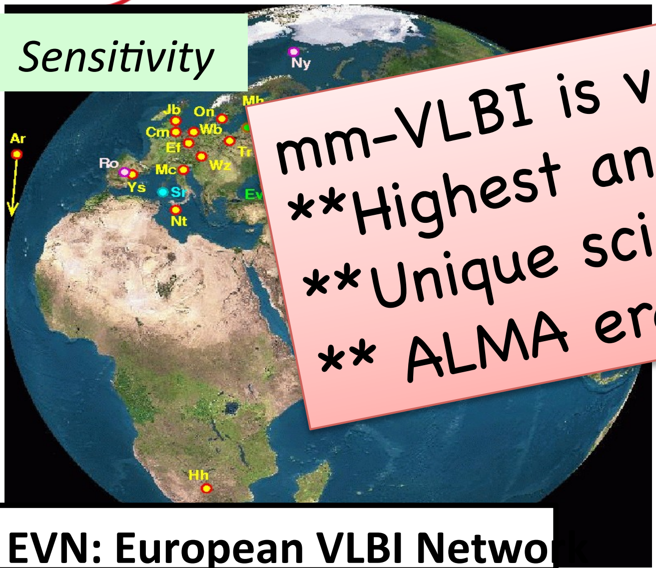
LBA Long Baseline Array

<~ 22GHz

VLBI NETWORKS

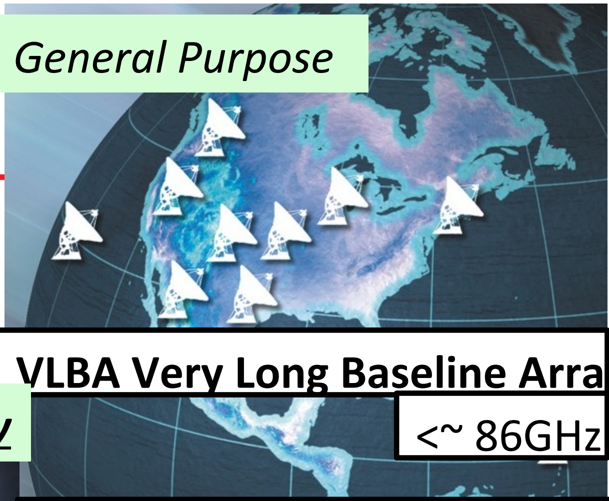
mm-VLBI is very interesting!
**Highest angular resolution
**Unique science
** ALMA era

Sensitivity

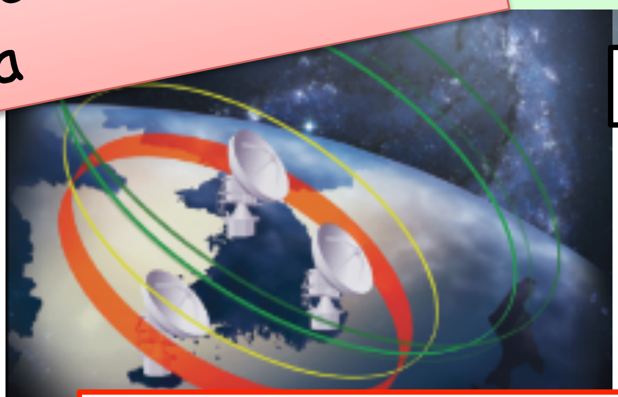


EVN: European VLBI Network
<~ 22GHz

General Purpose

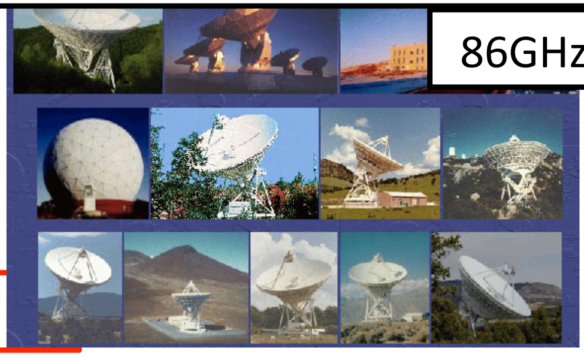


VLBA Very Long Baseline Array
<~ 86GHz



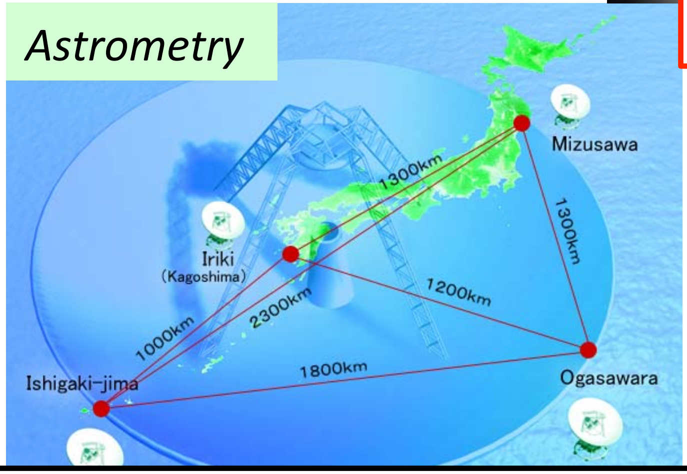
metry

KVN Korean VLBI Network
22/43/86/129 GHz



GMVA Global mm VLBI Array
86GHz

Astrometry



VERA VLBI for Earth Rotation and Astrometry
22/43 GHz

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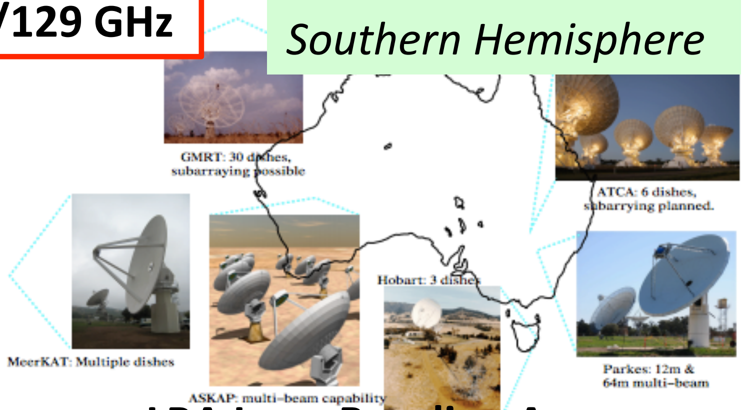
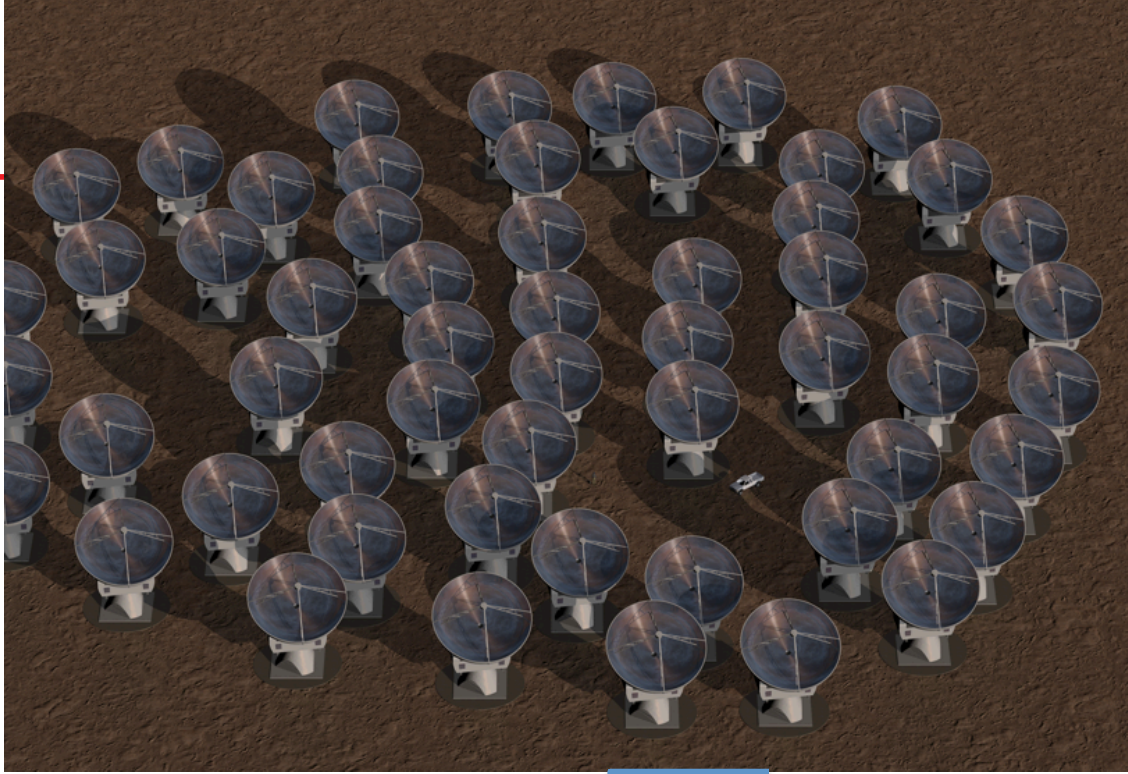


LBA Long Baseline Array
<~ 22GHz

But mm-VLBI is challenging…



<u>Limited Sensitivity:</u>

Limited aperture effici y

Receiver system t atures

Rapid tropos fluctuations α ν

➔ Shor spheric coherence time

Sour ntrinsically weaker, in general

HANDFUL OF TARGETS

Improve Performance
by reducing threshold of
detected flux (ΔS):

$$\downarrow \Delta S_{ij} = \frac{1}{\eta_s} \times \sqrt{\frac{SEFD_i \times SEFD_j}{2 \times \Delta\nu \times \tau_{Coh.}}}$$

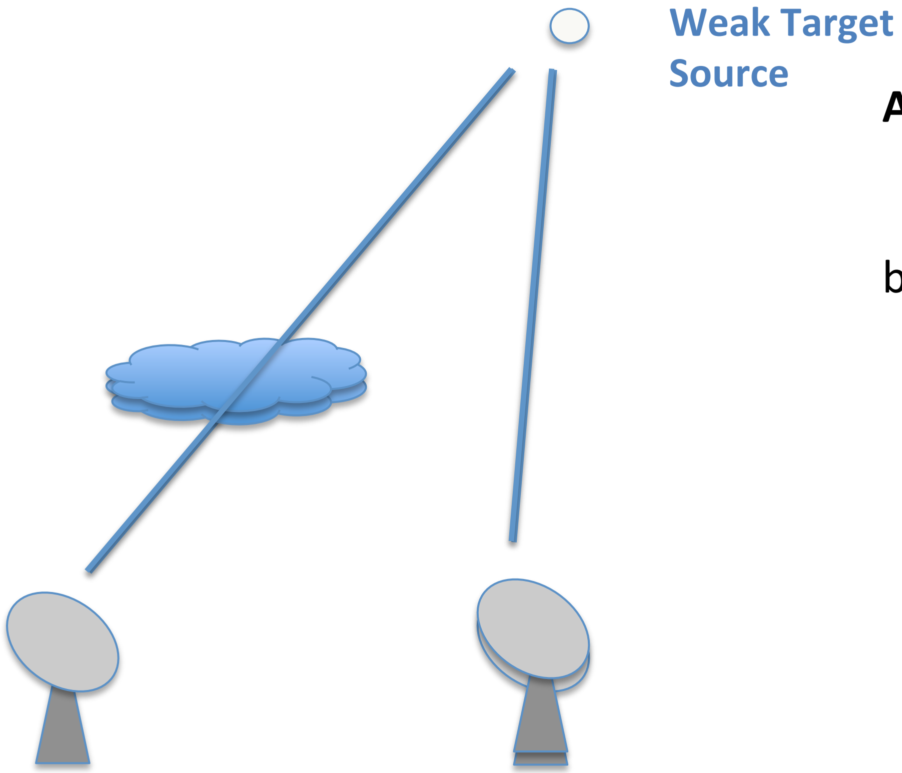
Smaller SEFD through
Huge Collecting Area,

INCREASING coherent Integration Time
Through superior tropospheric calibration

GOAL: Higher sensitivity ➔ wider applicability

Phase Referencing
"trans-source"

PR @ 22 GHz



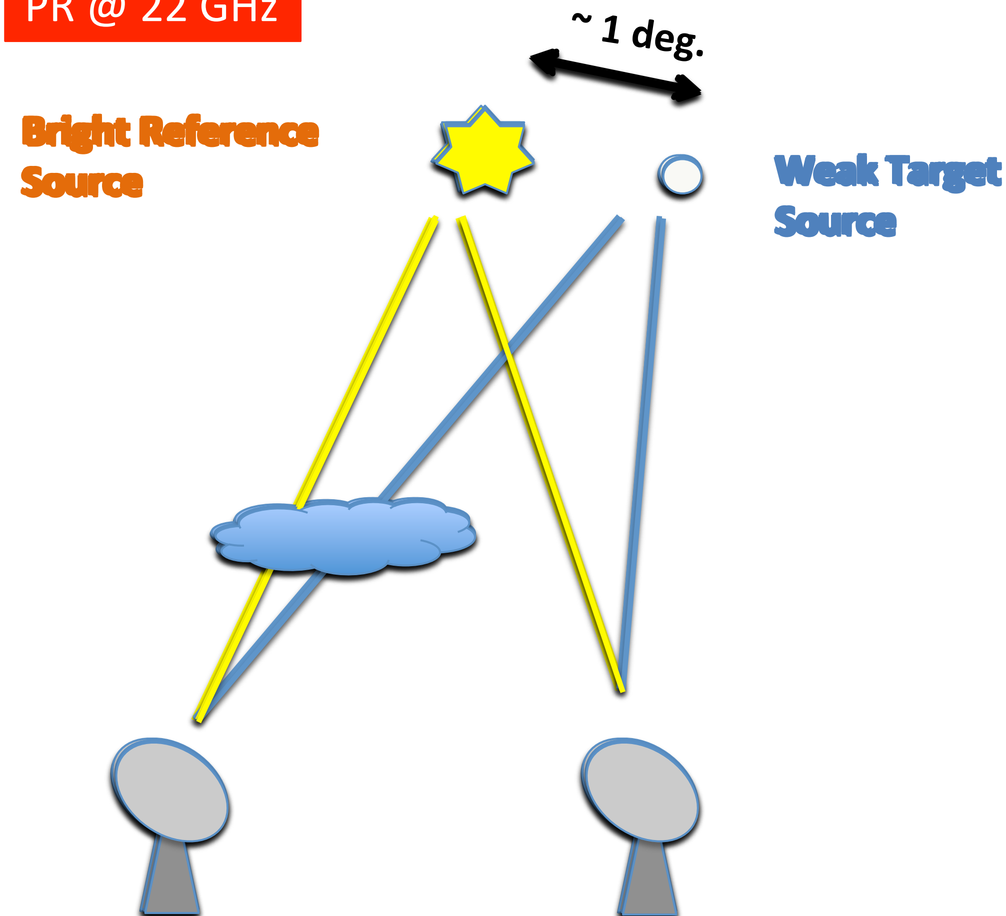
AIM: Improve performance of cm-VLBI,

1) Higher sensitivity (micro-Jy sources),
2) high precision astrometry (micro-as)

by correcting for tropospheric fluctuations.

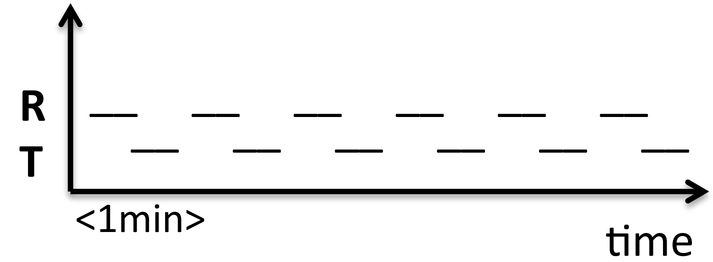
Phase Referencing
"trans-source"

PR @ 22 GHz



WEAK SOURCES
ASTROMETRY

Duty Cycle @ 22 GHz



AIM: Improve performance of cm-VLBI,
1) Higher sensitivity, and
2) high precision astrometry
by correcting for tropospheric fluctuations.

STRATEGY:

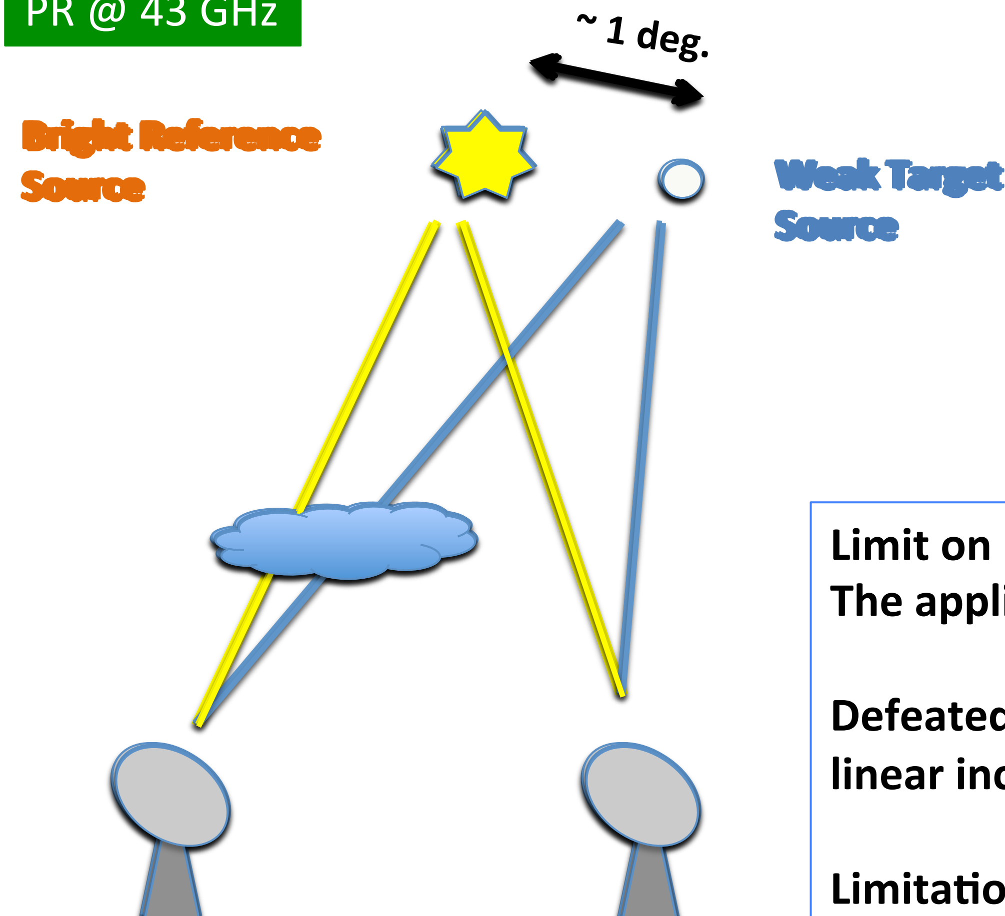
1)Use interleaving observations of a nearby reference source to correct for the errors And then coherently add the signal of the Target source beyond trop. coherence time.

2)Temporal and Spatial interpolation.

3)Telescope switching fully samples tropospheric changes

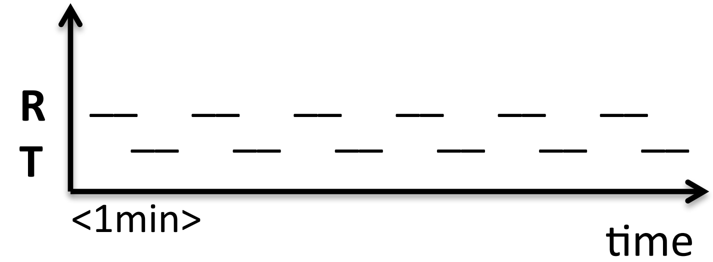
Phase Referencing
"trans-source"

PR @ 43 GHz

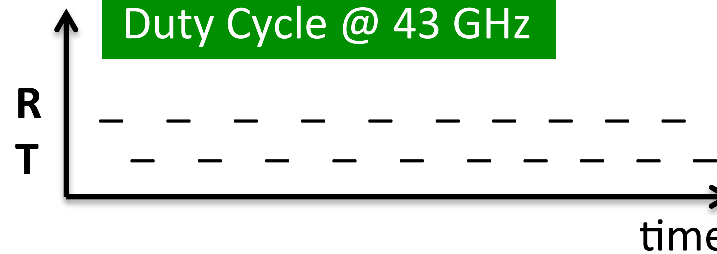


WEAK SOURCES
ASTROMETRY

Duty Cycle @ 22 GHz



Duty Cycle @ 43 GHz



Limit on how fast a telescope can move constrains The application to 43 GHz or below (in general).

Defeated by rapid phase tropospheric fluctuations, linear increase with frequency (non-dispersive)

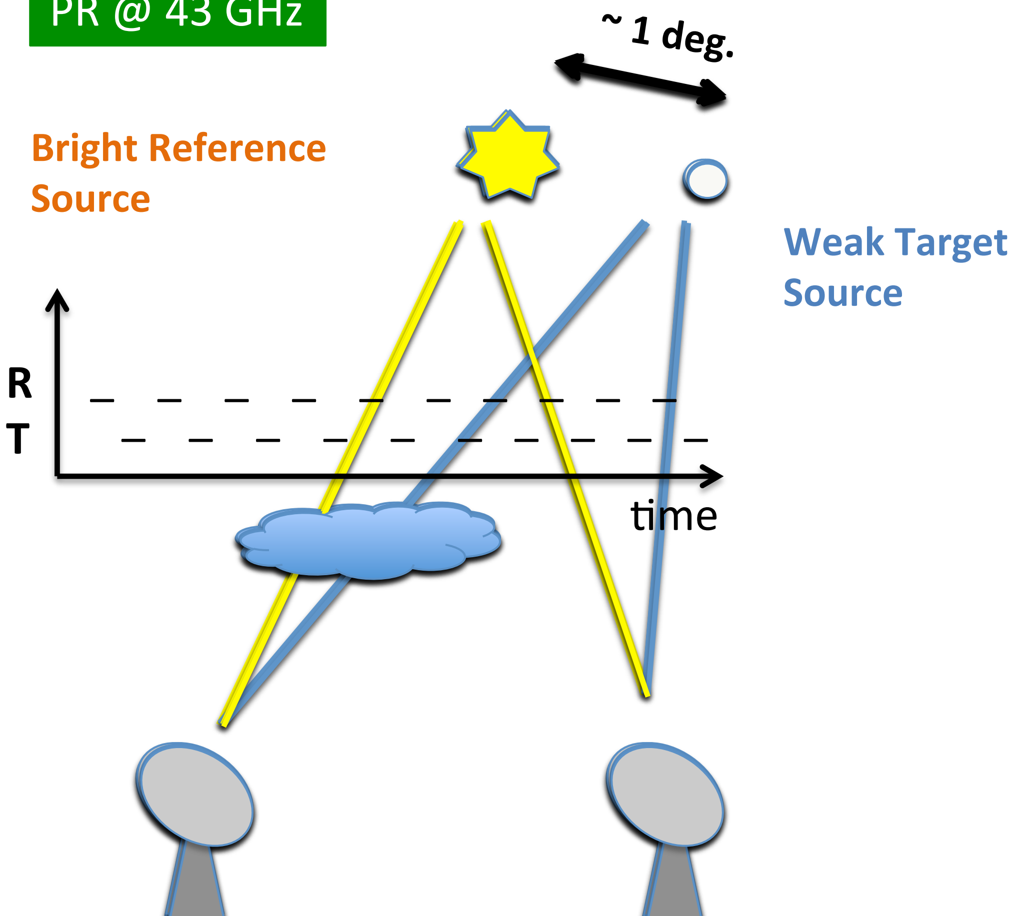
Limitations in performance start at freq. > 43 GHz

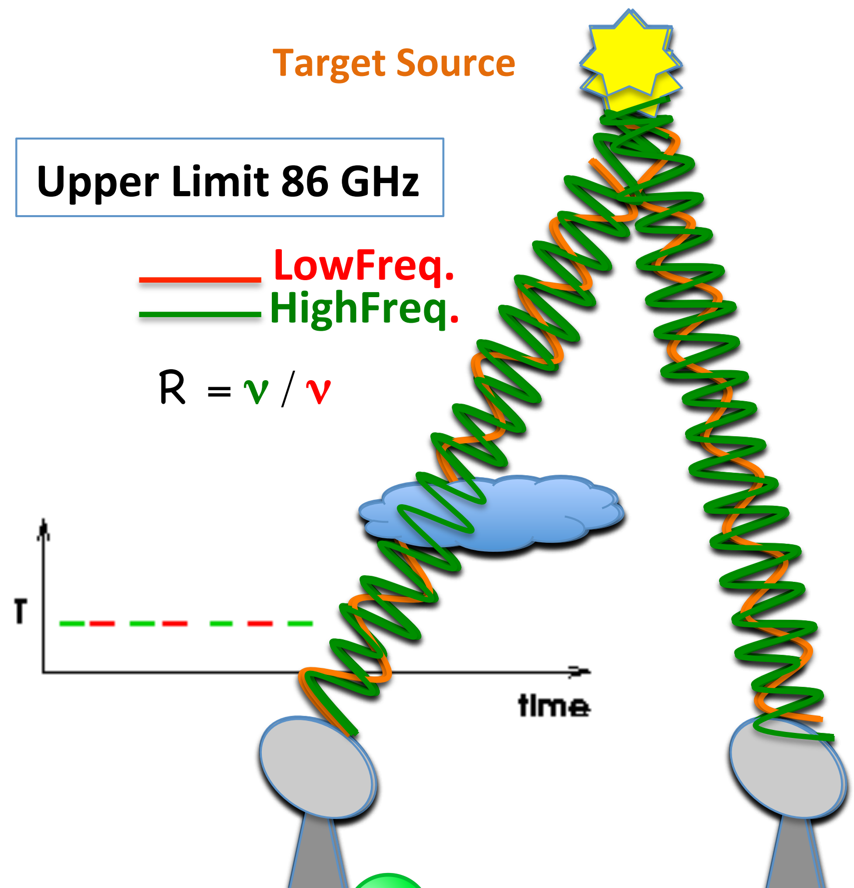
Phase Referencing *"trans-source"*

Paradigm Shift: "trans-frequency" calibration

"fast-frequency switching" with VLBA

PR @ 43 GHz





WEAK SOURCES ✔

ASTROMETRY ✔

WEAK SOURCES ✔

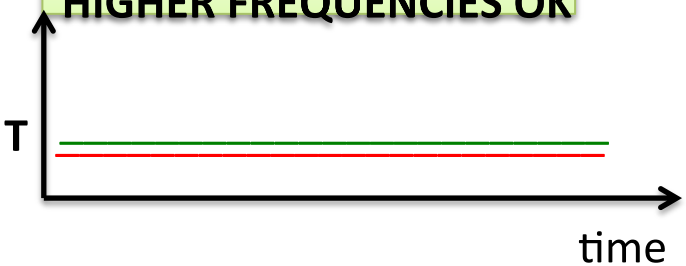
ASTROMETRY ✘

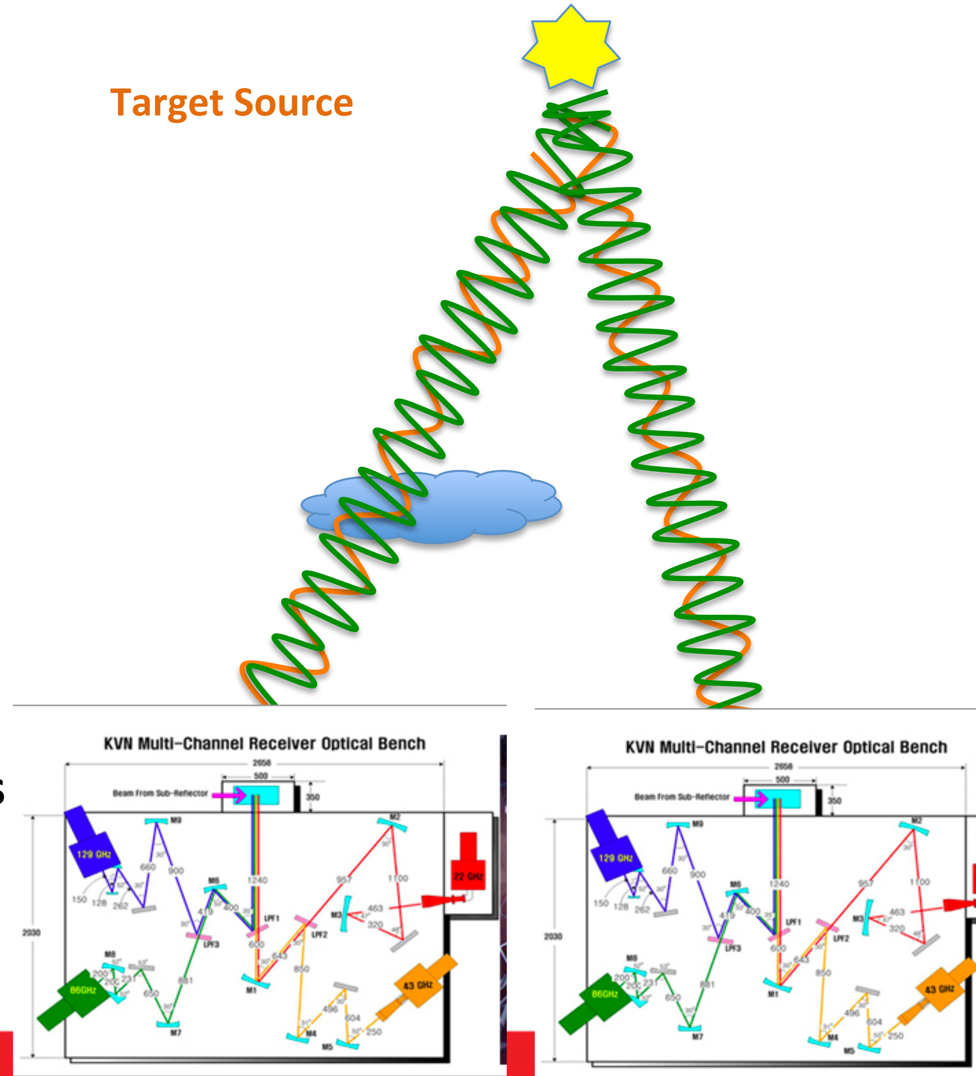
Middelberg et al. 2005

Rioja&Dodson 2008,2011

ALTERNATIVE APPROACH FOR SUPERIOR TROPOSPHERIC COMPENSATION

BETTER SIMULTANEOUS!
HIGHER FREQUENCIES OK





1) No interpolation is required
2) Applicable to higher frequencies

Multi-Channel KVN receivers

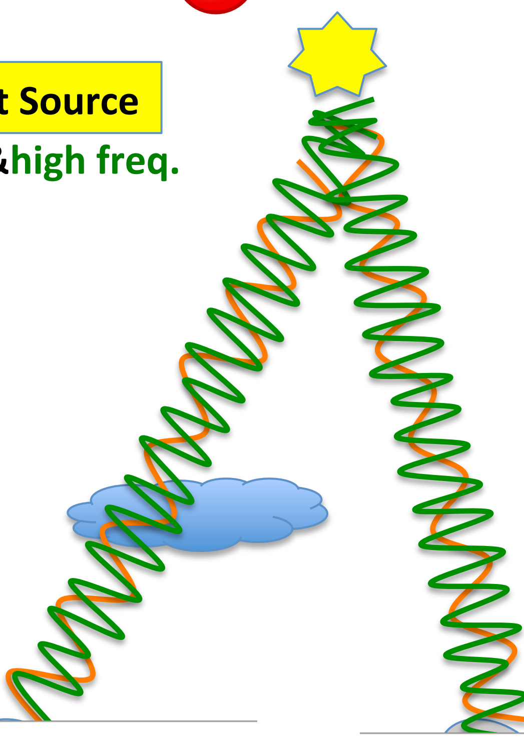
WEAK SOURCES ✓
ASTROMETRY ✗

Frequency Phase Referencing (FPT)

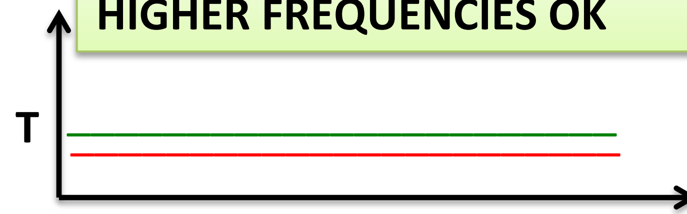
WEAK SOURCES ASTROMETRY

Target Source

@low&high freq.



BETTER (near) SIMULTANEOUS!
HIGHER FREQUENCIES OK

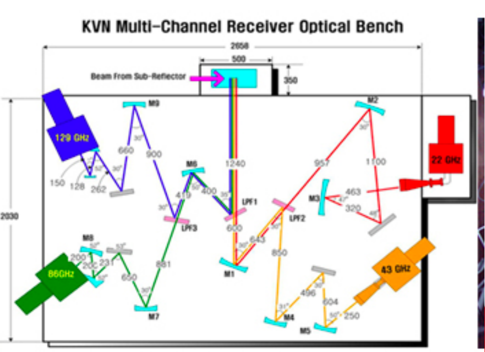


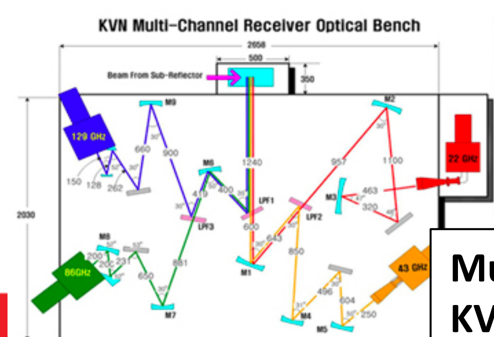
$$R = \nu / \nu$$

Fast Slow Slow

$$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + \phi_{A,STR} + 2\pi n_A$$

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





Multi-channel KVN receivers

Korea Astronomy and Space Science Institute

Frequency Phase Referencing (FPT)

WEAK SOURCES
ASTROMETRY

Target Source
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BETTER (near) SIMULTANEOUS!
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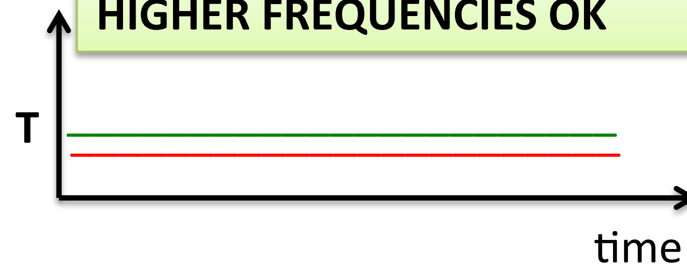
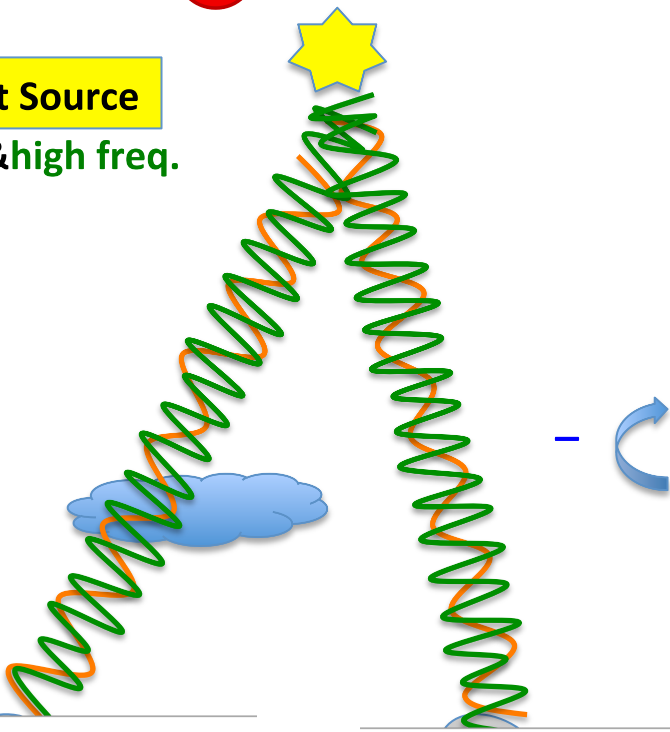




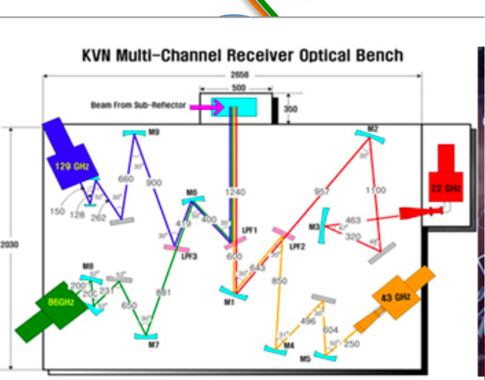
$R = \nu / \nu$

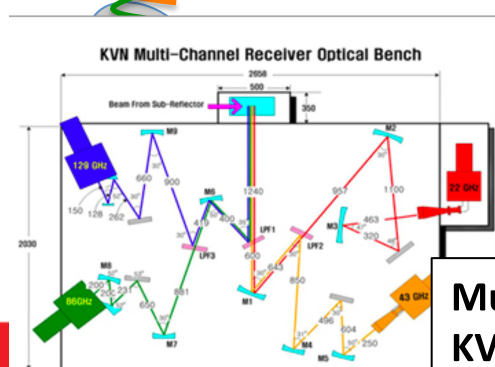
Fast　Slow　Slow

$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + \phi_{A,STR} + 2\pi n_A$

$-$

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





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ASTROMETRY ✗

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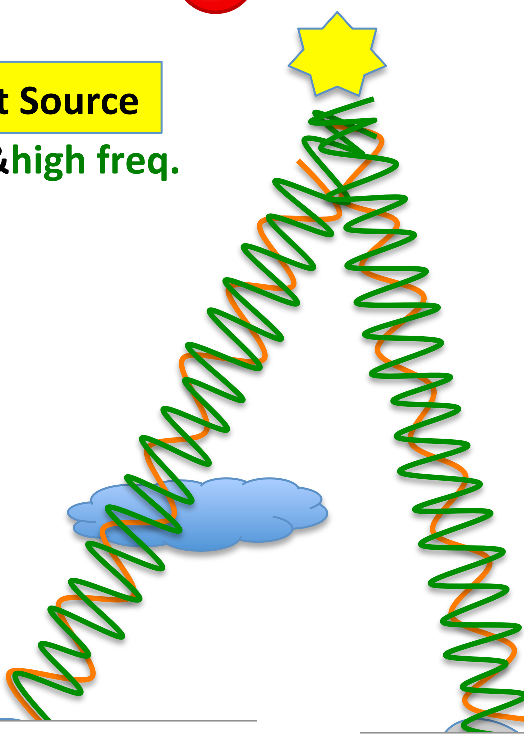
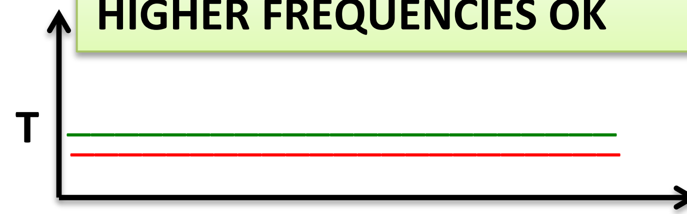


BETTER (near) SIMULTANEOUS!
HIGHER FREQUENCIES OK



$R = \nu / \nu$

Fast Slow Slow

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

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

Non-dispersive Errors:

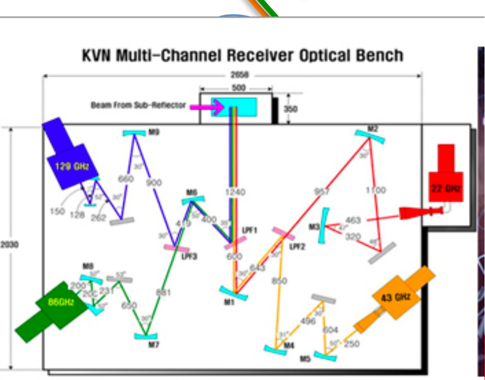
$\phi_{A,TRO} - R * \phi_{A,TRO} = 0$

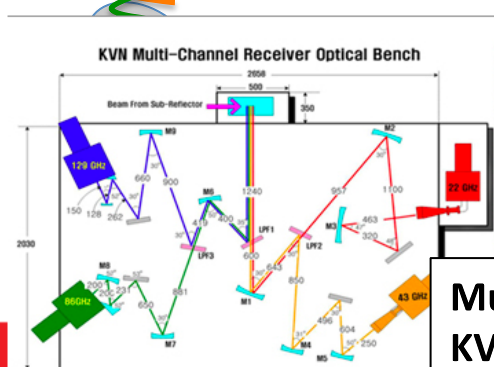
$\phi_{A,GEO} - R * \phi_{A,GEO} = 0$

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)

<u>OUTCOME:</u> **PRECISE CALIBRATION OF THE TROPOSHERE**
(and in general any non-dispersive residuals)

<u>ENABLES</u>: **EXTENDED COHERENCE TIME**

- ➔ **WEAK SOURCE DETECTION <u>AT HIGH FREQUENCIES</u>**
- ➔ **~~ASTROMETRY~~**

**** (near) SIMULTANEOUS multi-frequency observations required for high freqs.***

Korea Astronomy and Space Science Institute

The Quest of Astrometry…

Source Frequency Phase Referencing (SFPR)

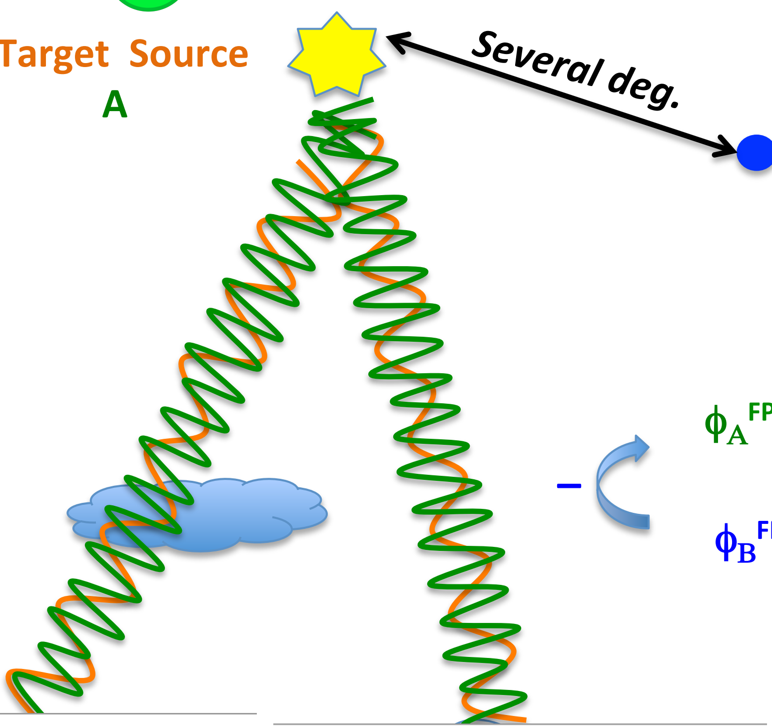
WEAK SOURCES ✔

ASTROMETRY ✔

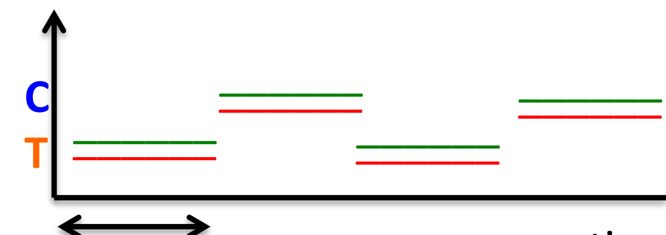
SFPR: Rioja & Dodson '08,'11,'14,'15

(TWO SOURCES)

Target Source
A



Reference
Source
B



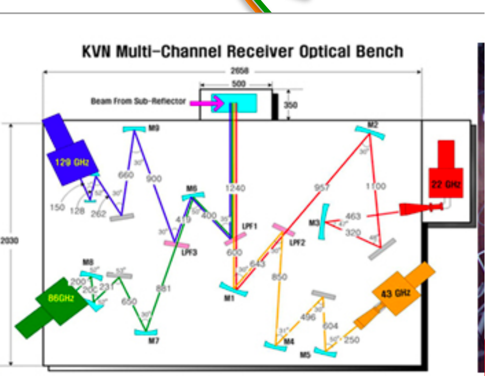
$R = \nu / \nu$

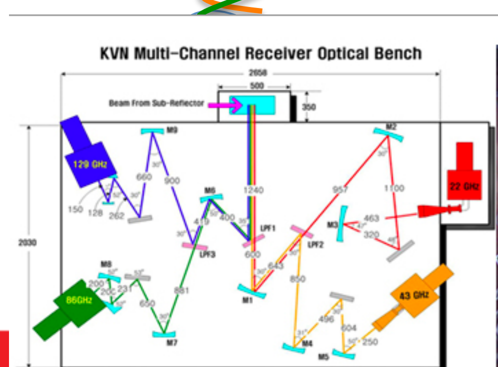
Fast Slow Slow

$\phi_A^{FPT} = \phi_{[illegible]EO} + \phi_{[illegible]O} + \phi_{A,ION} + \phi_{A,INST} + \phi''_{A,STR} + 2\pi n_A$

$-$

$\phi_B^{FPT} = \phi_{[illegible]EO} + \phi_{[illegible]O} + \phi_{B,ION} + \phi_{B,INST} + \phi'_{B,STR} + 2\pi n_B$





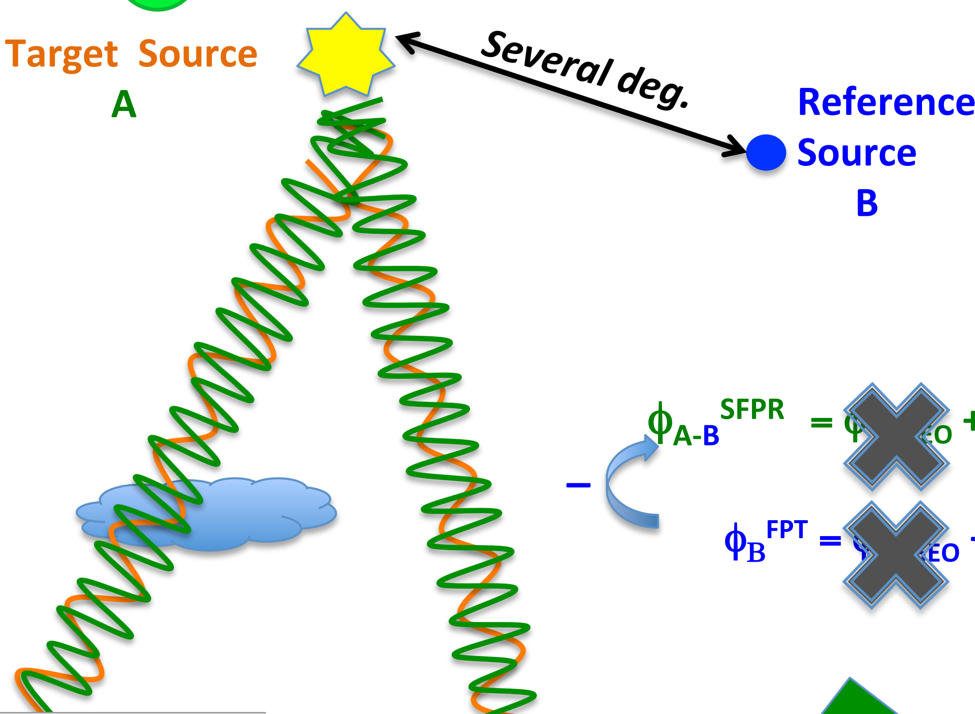
KVN

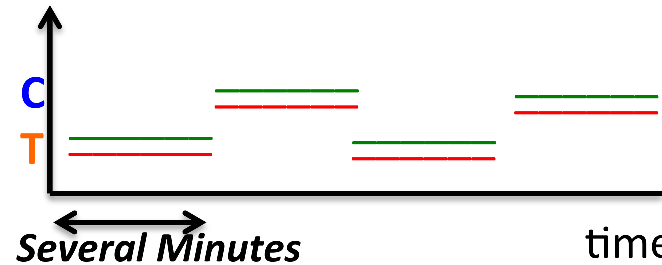
Source Frequency Phase Referencing (SFPR)

WEAK SOURCES ✓
ASTROMETRY ✓

SFPR: Rioja & Dodson '08,'11,'14,'15

(TWO SOURCES)





$R = \nu / \nu$

Fast Slow Slow

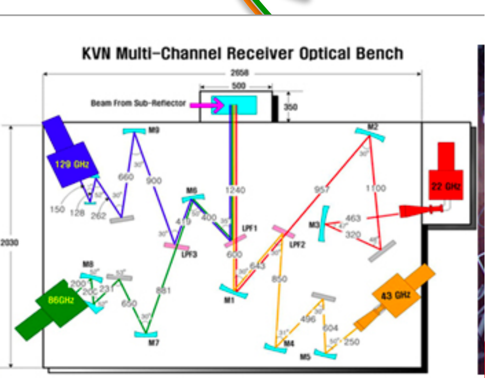
$\phi_{A-B}^{SFPR} = \phi$ ✕ $_{EO} + \phi$ ✕ $_{O} + \phi$ ✕ $_{N} + \phi$ ✕ $_{T} + \phi''_{A,STR} + 2\pi n_A$

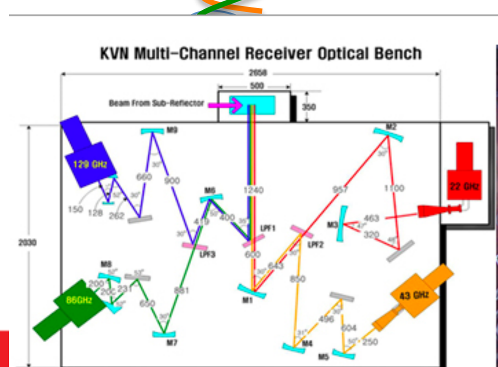
$-$

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

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

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





KVN

Astrometry:

ϕ_{A-B}^{SFPR} ←FFT→ **SFPRed A-Map at high freq.**

Source Frequency Phase Referencing (SFPR)

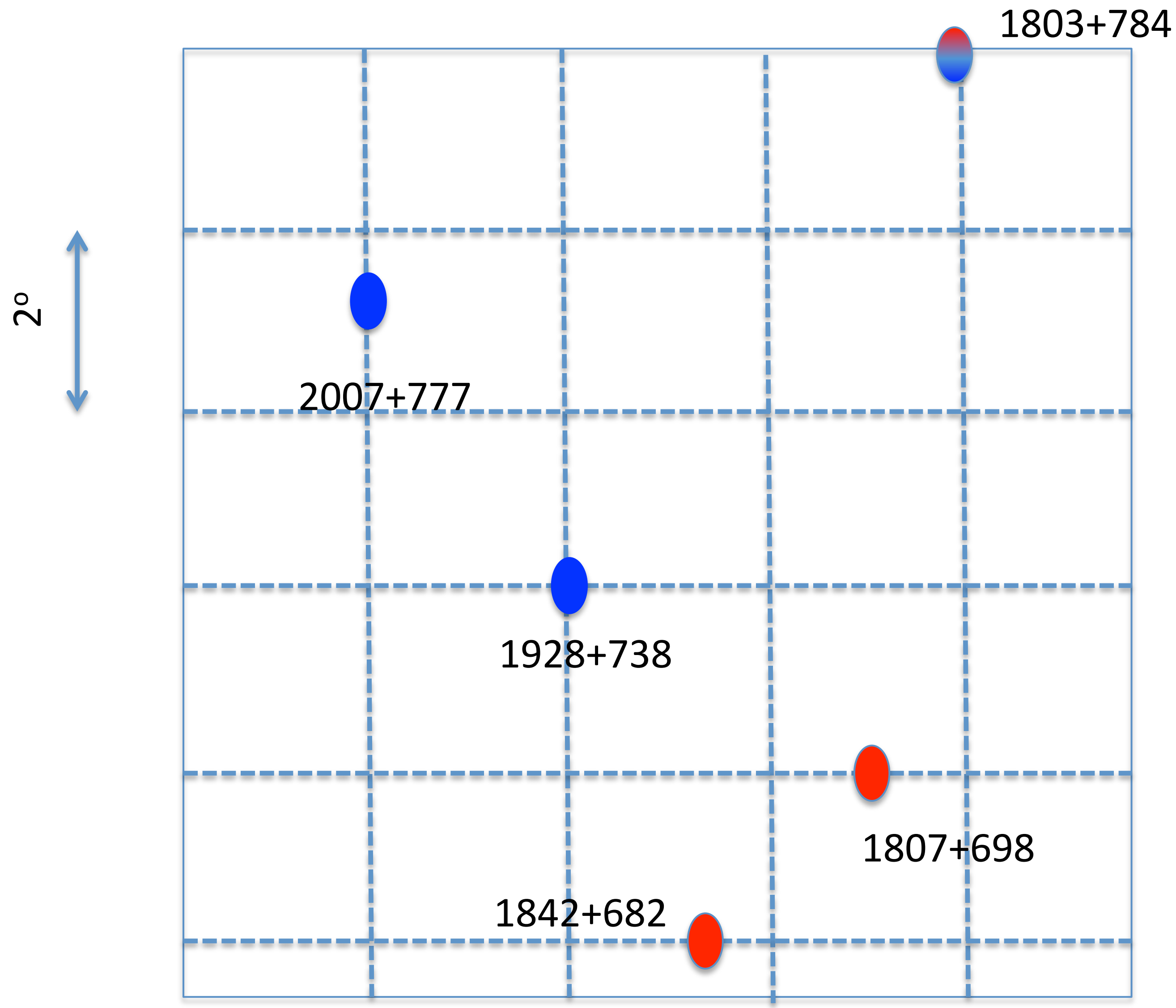
OUTCOME: **PRECISE ATMOSPHERIC & INSTR. CALIBRATION, WHILE KEEPING ASTROMETRIC SIGNATURE**

ENABLES: **EXTEND COHERENCE TIME & ASTROMETRY AT HIGH FREQS**

- ➔ **WEAK SOURCE DETECTION**
- ➔ **ASTROMETRY (frequency dependent position shifts: continuum & lines; registration of images at multiple frequencies)**

*Slow antenna switching OK
*Several degrees source separation OK
** (near)SIMULTANEOUS multi-frequency observations required for high freqs.*

Empirical Demonstration: 4-band KVN SFPR observations of 5 AGNs

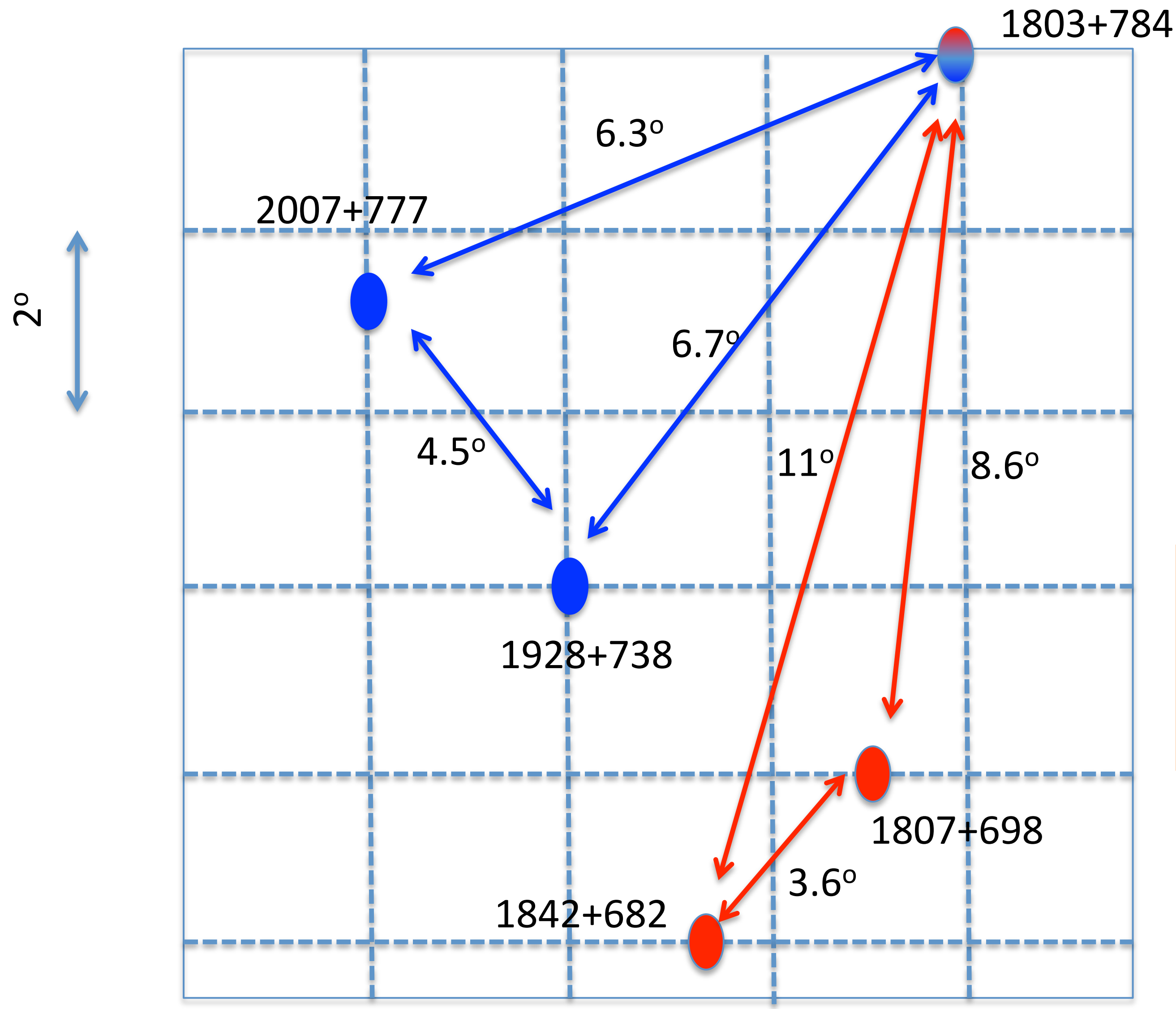


Triangle 1
Triangle 2

22,43,86,130 GHz
K,Q,W,D bands

(Rioja,Dodson+'15)

Empirical Demonstration:
4-band KVN SFPR observations of 5 AGNs



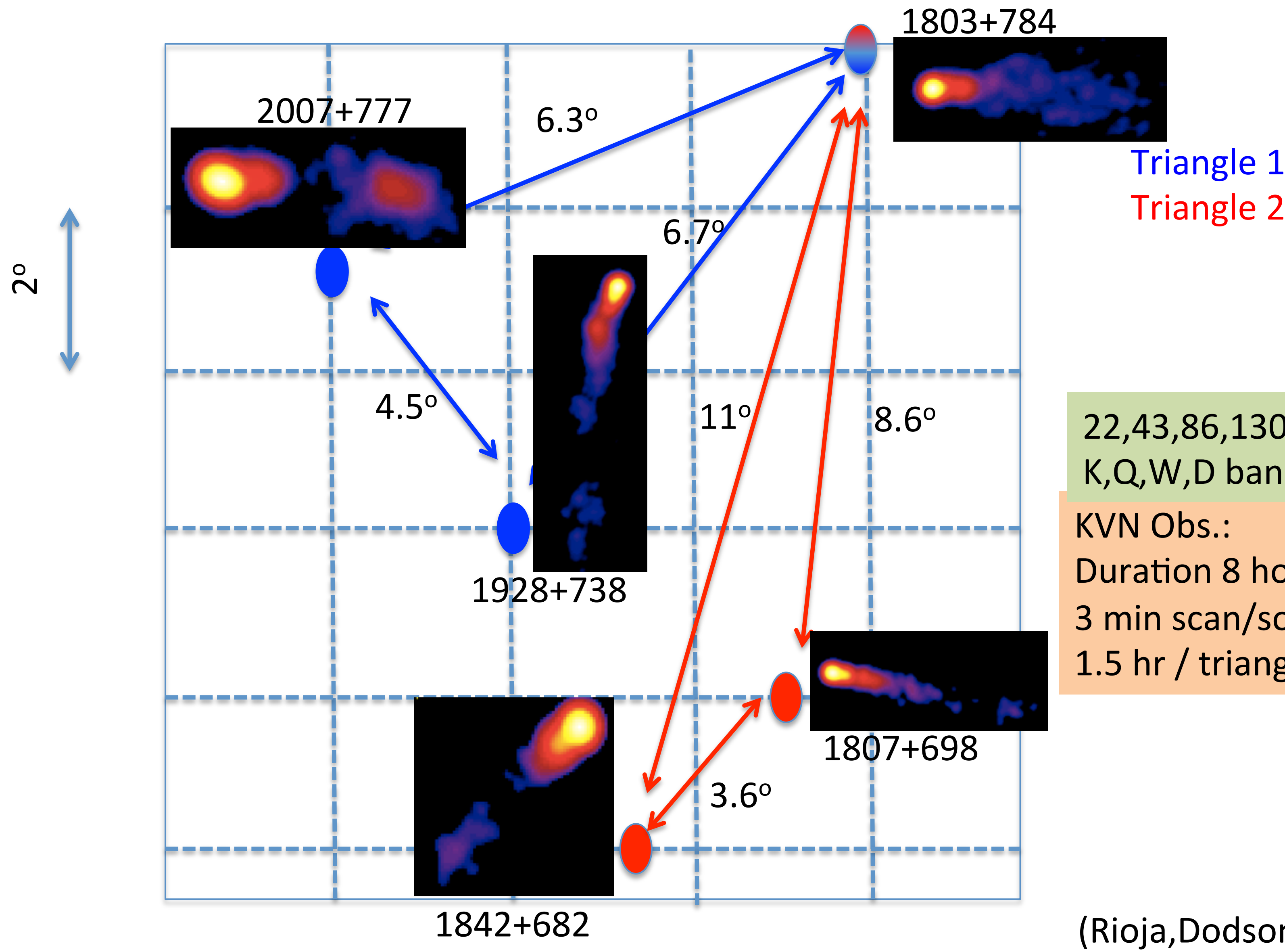
Triangle 1
Triangle 2

22,43,86,130 GHz
K,Q,W,D bands

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

(Rioja,Dodson+'15)

Empirical Demonstration:
4-band KVN SFPR observations of 5 AGNs



22,43,86,130 GHz
K,Q,W,D bands

KVN Obs.:
Duration 8 hours
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(Rioja,Dodson+'15)

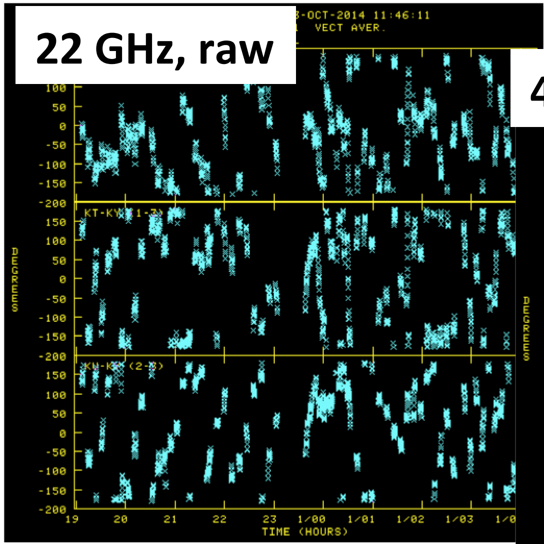
Empirical Demonstration:
4-band KVN SFPR observations of 5 AGNs

(1) Outcomes: Effective Tropospheric Compensation

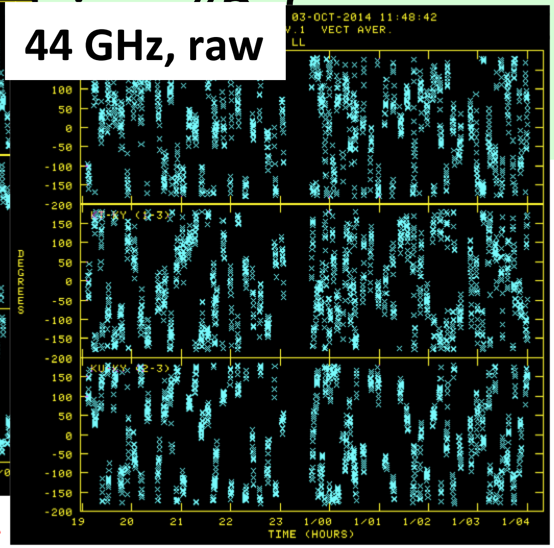
FPT analysis – "2-frequencies"

ies”

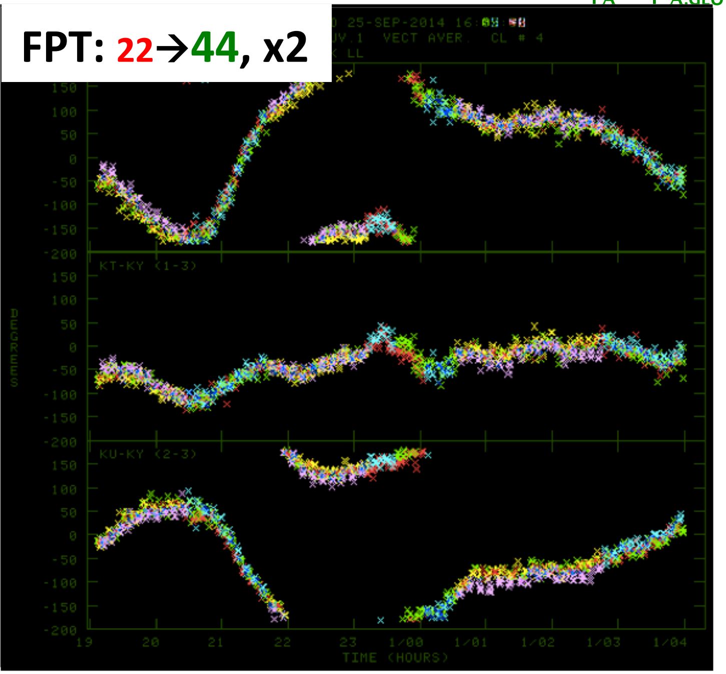
for a given ν_{low} (22GHz)



$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n$



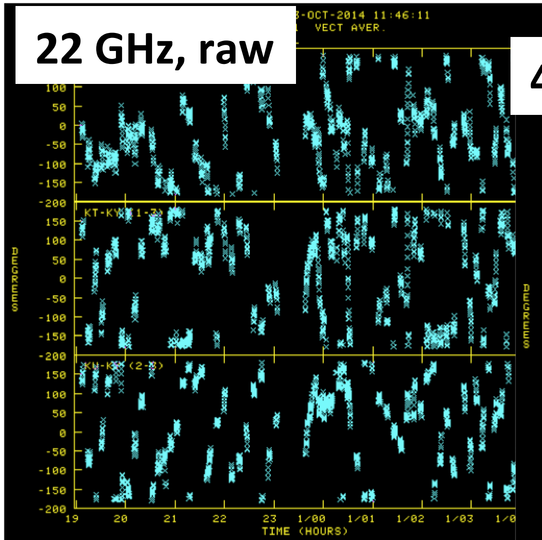
$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A$



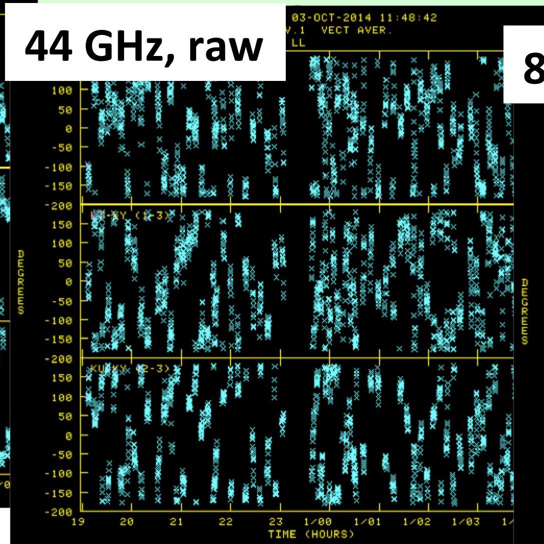
$\phi_A - 2 * \phi_A$

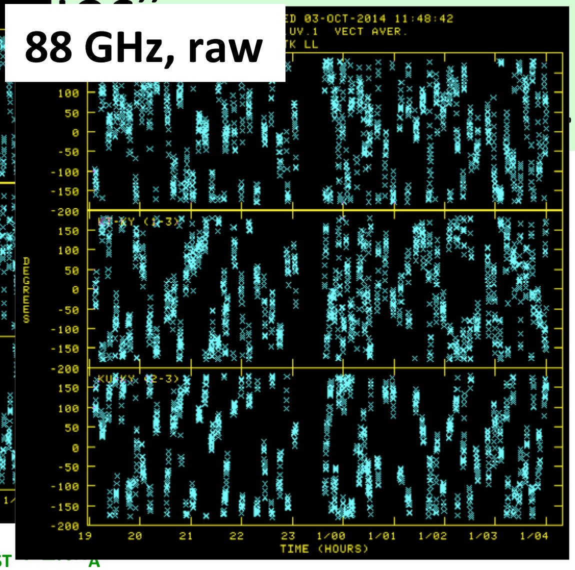
…ies”

…2GHz)

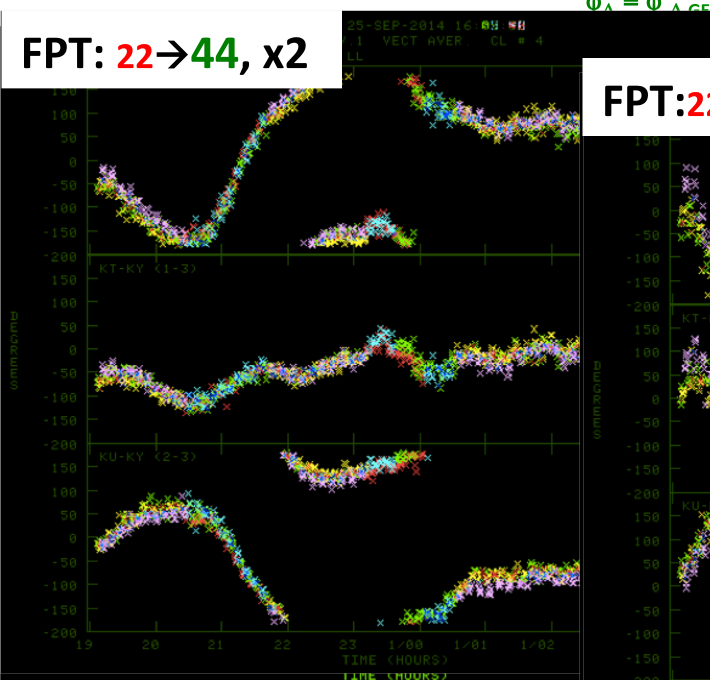


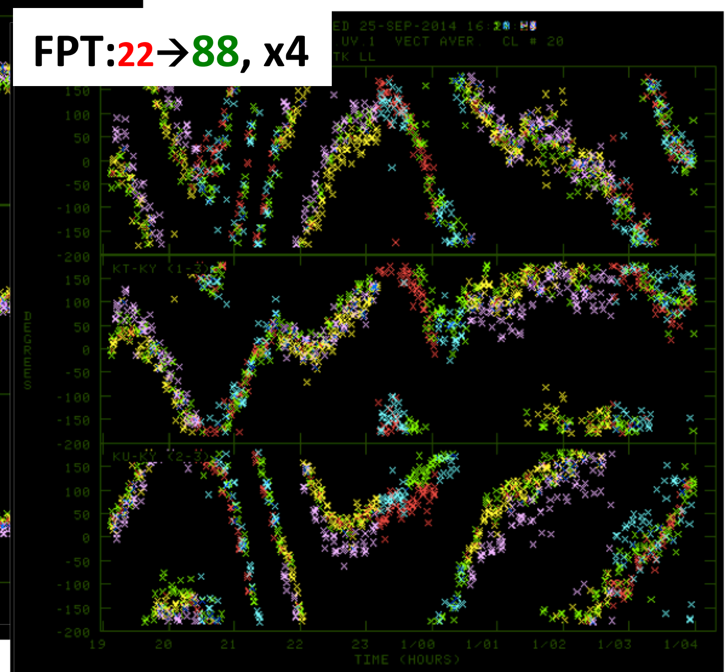
$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n$

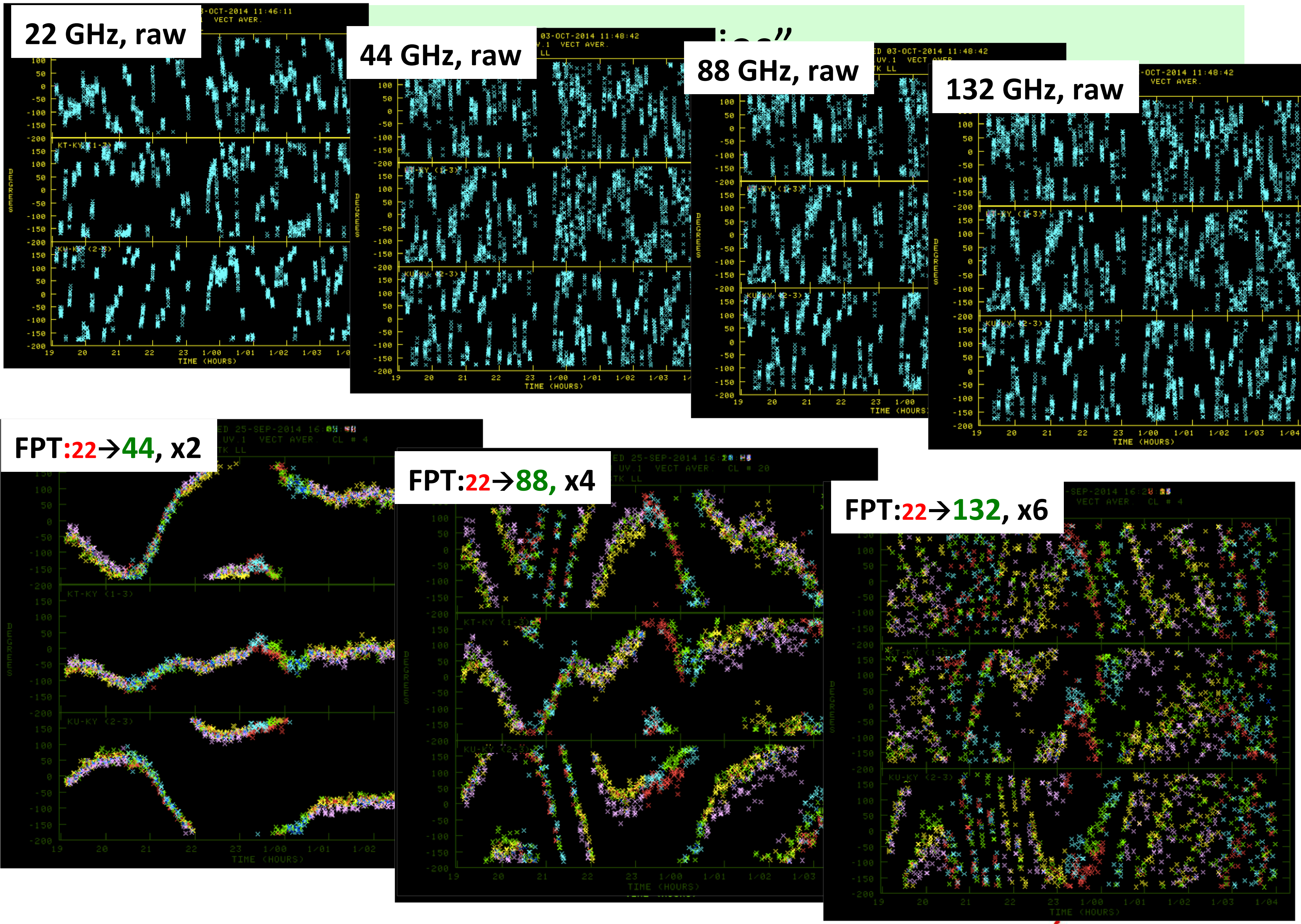




$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST}$ …

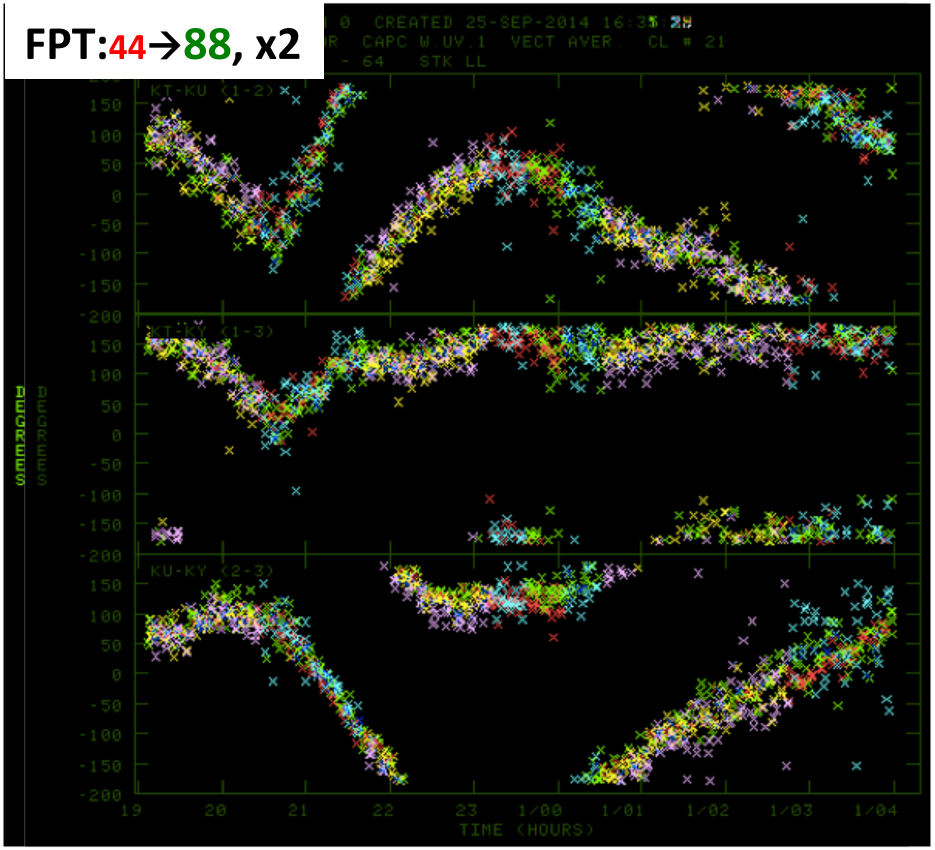




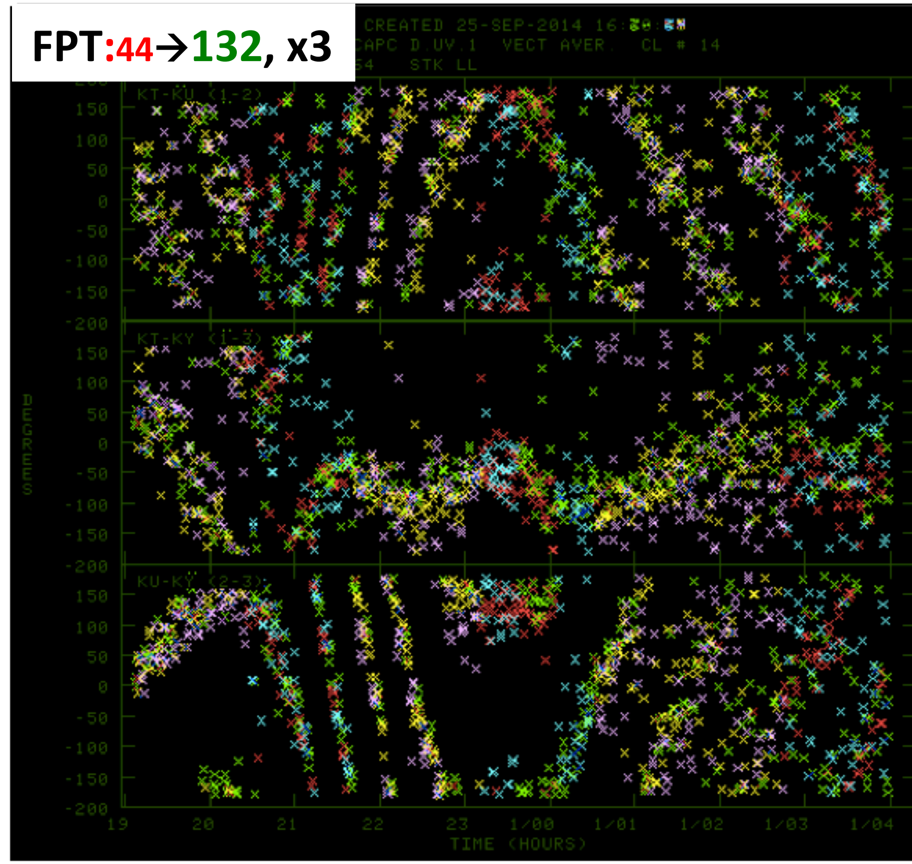

22 GHz, raw
44 GHz, raw
88 GHz, raw
132 GHz, raw
FPT:22→44, x2
FPT:22→88, x4
FPT:22→132, x6
TIME (HOURS)
DEGREES
KT-KY (1-3)
KU-KY (2-3)

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

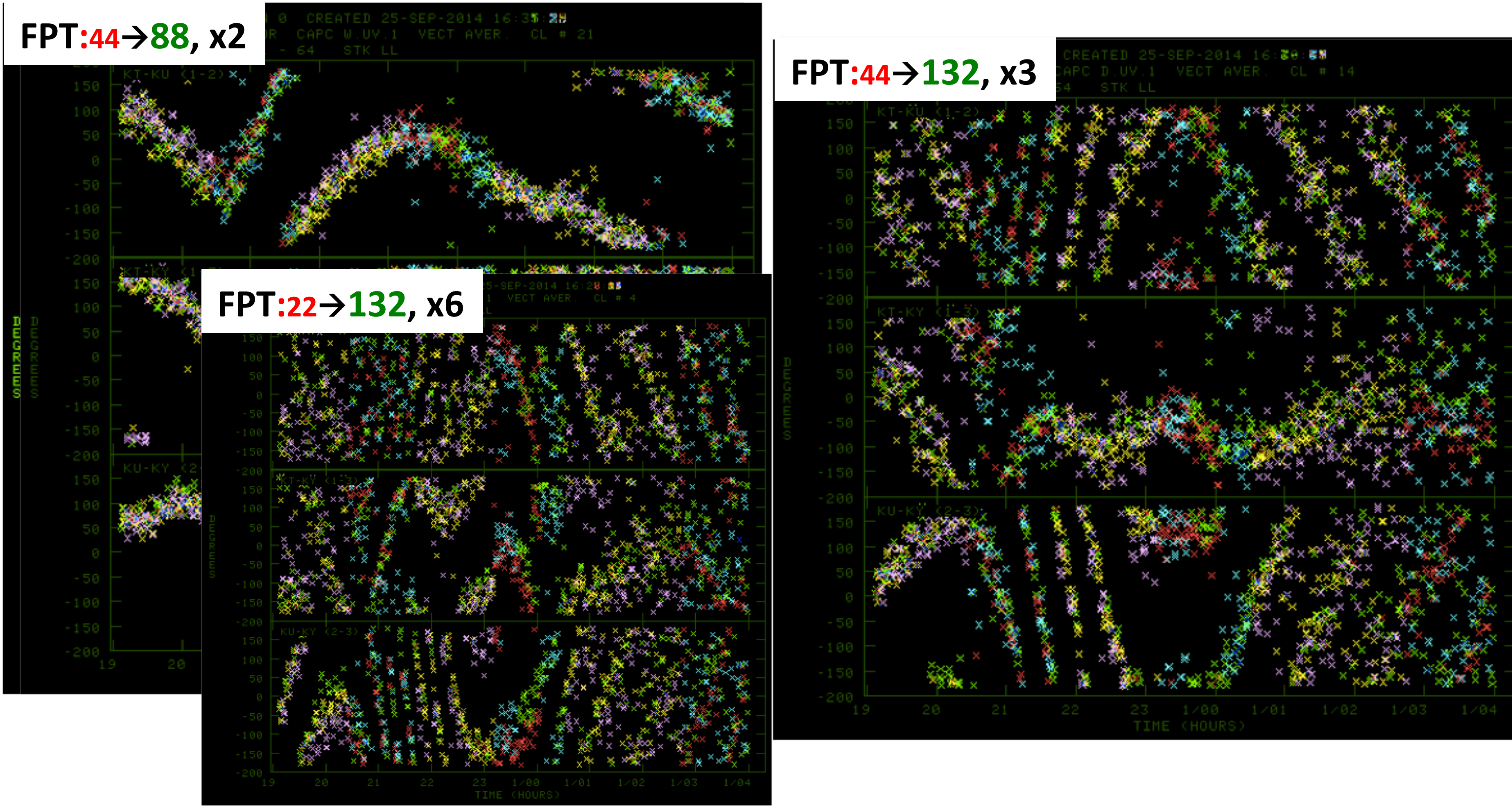
FPT:44→88, x2



FPT:44→132, x3

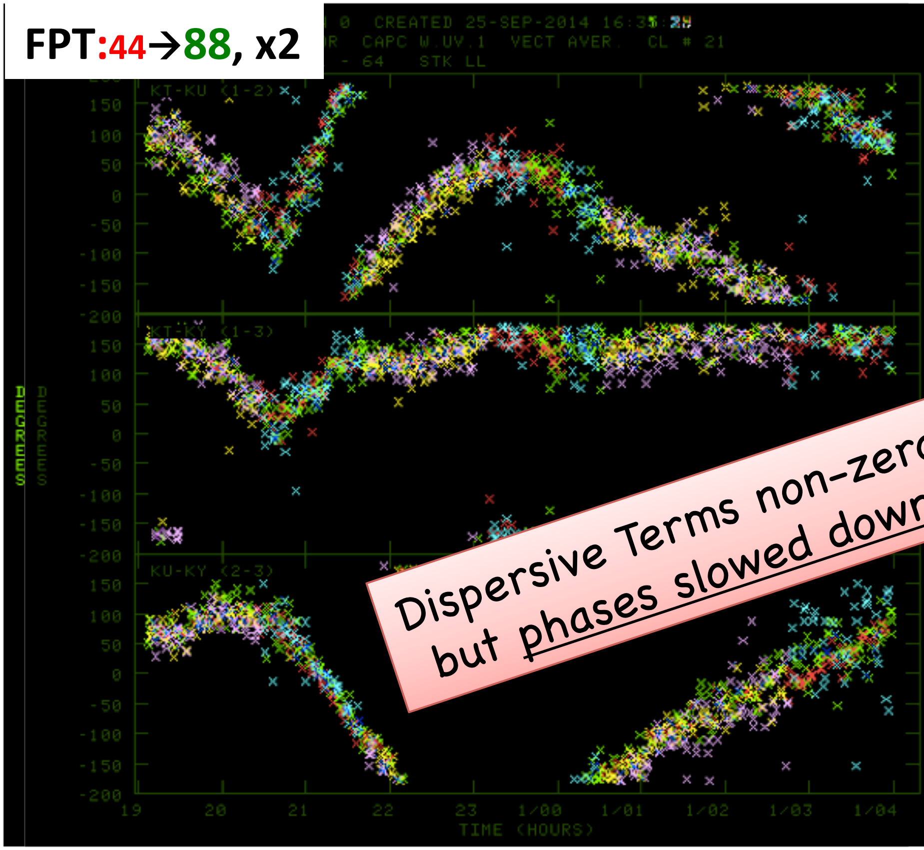


FPT analysis – “2-frequencies”
Residuals increase with R, for a given ν_{low} (44 GHz)

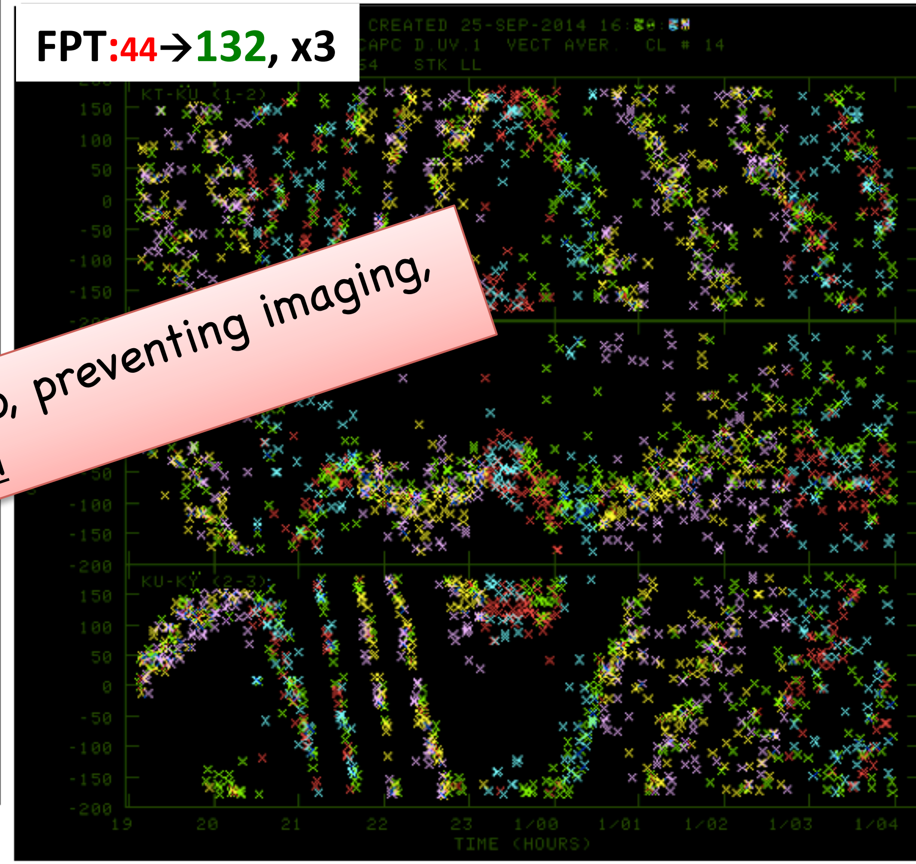


FPT analysis – "2-frequencies"
Residuals increase with R, for a given ν_{low} (44 GHz)

FPT:44→88, x2



FPT:44→132, x3



Dispersive Terms non-zero, preventing imaging,
but phases slowed down

$R = \nu / \nu$

Fast Slow Slow

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

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

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Empirical Demonstration:
4-band KVN SFPR observations of 5 AGNs

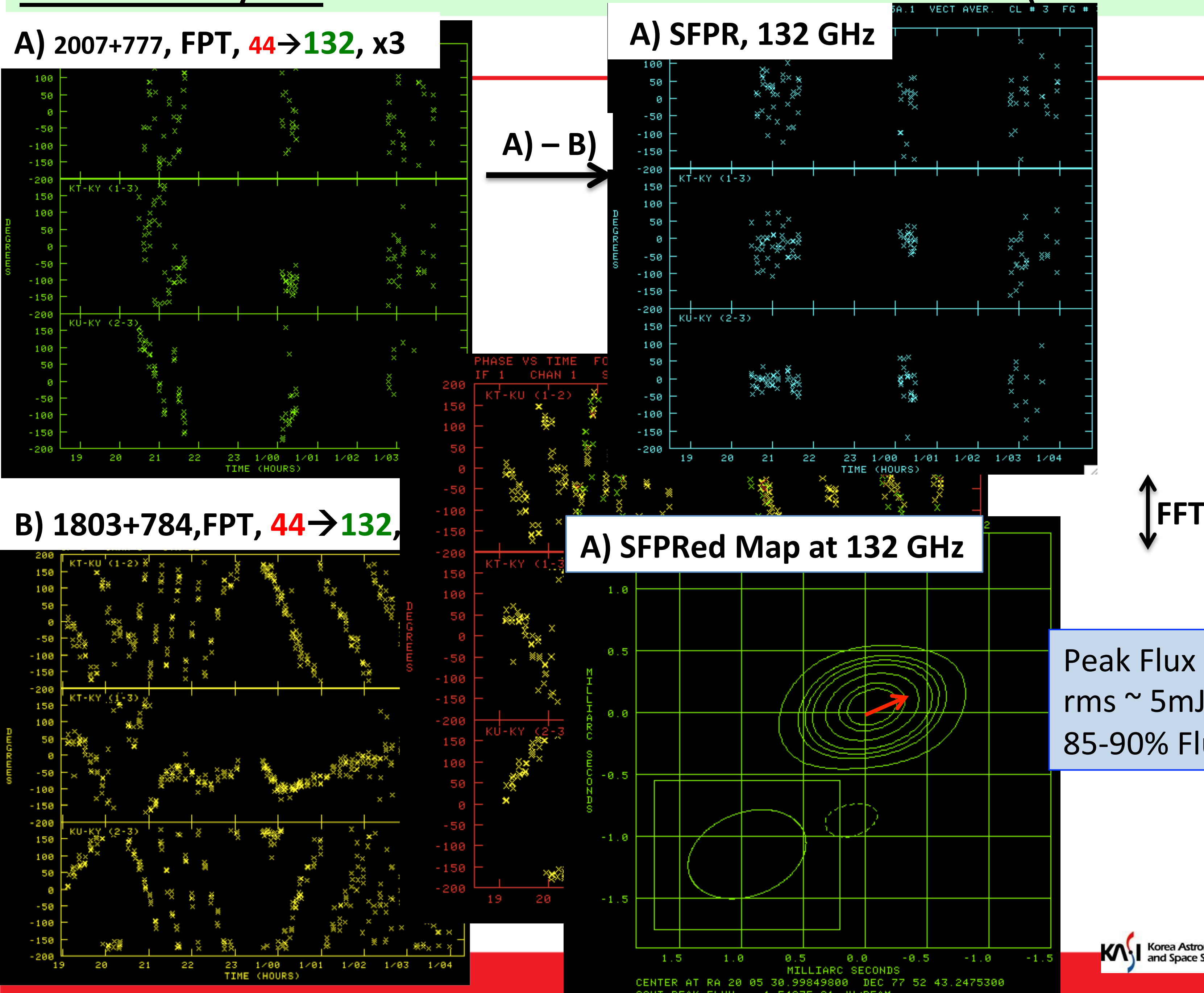
(1) Outcomes: Effective Troposheric Compensation

FPT analysis – "2-frequencies"

(2) Outcomes: Astrometry

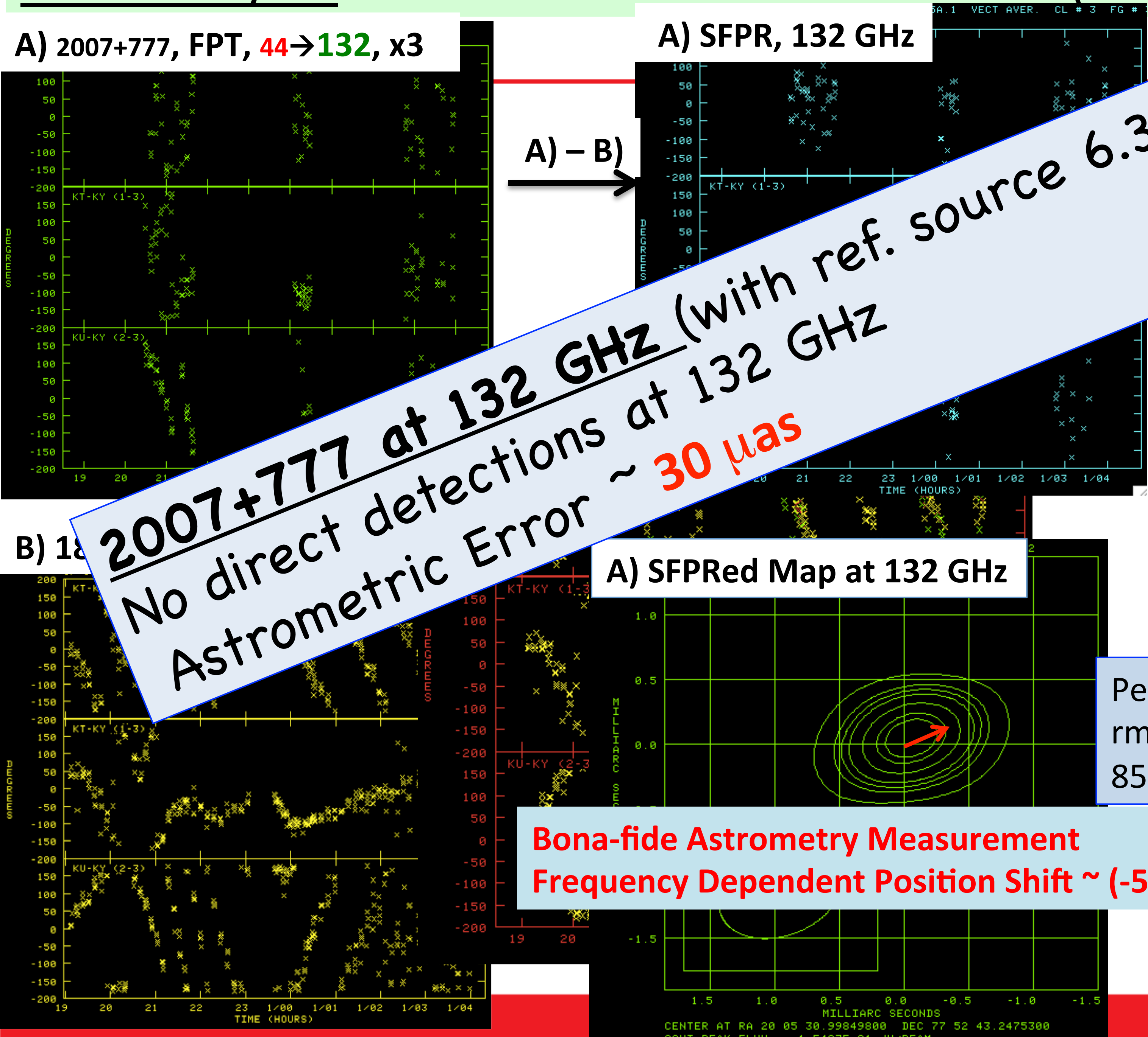
SFPR analysis – "2-frequencies" & "2 sources"

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



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

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



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

No direct detections at 132 GHz

Astrometric Error ~ 30 μas

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

Bona-fide Astrometry Measurement
Frequency Dependent Position Shift ~ (-50,+50) μas

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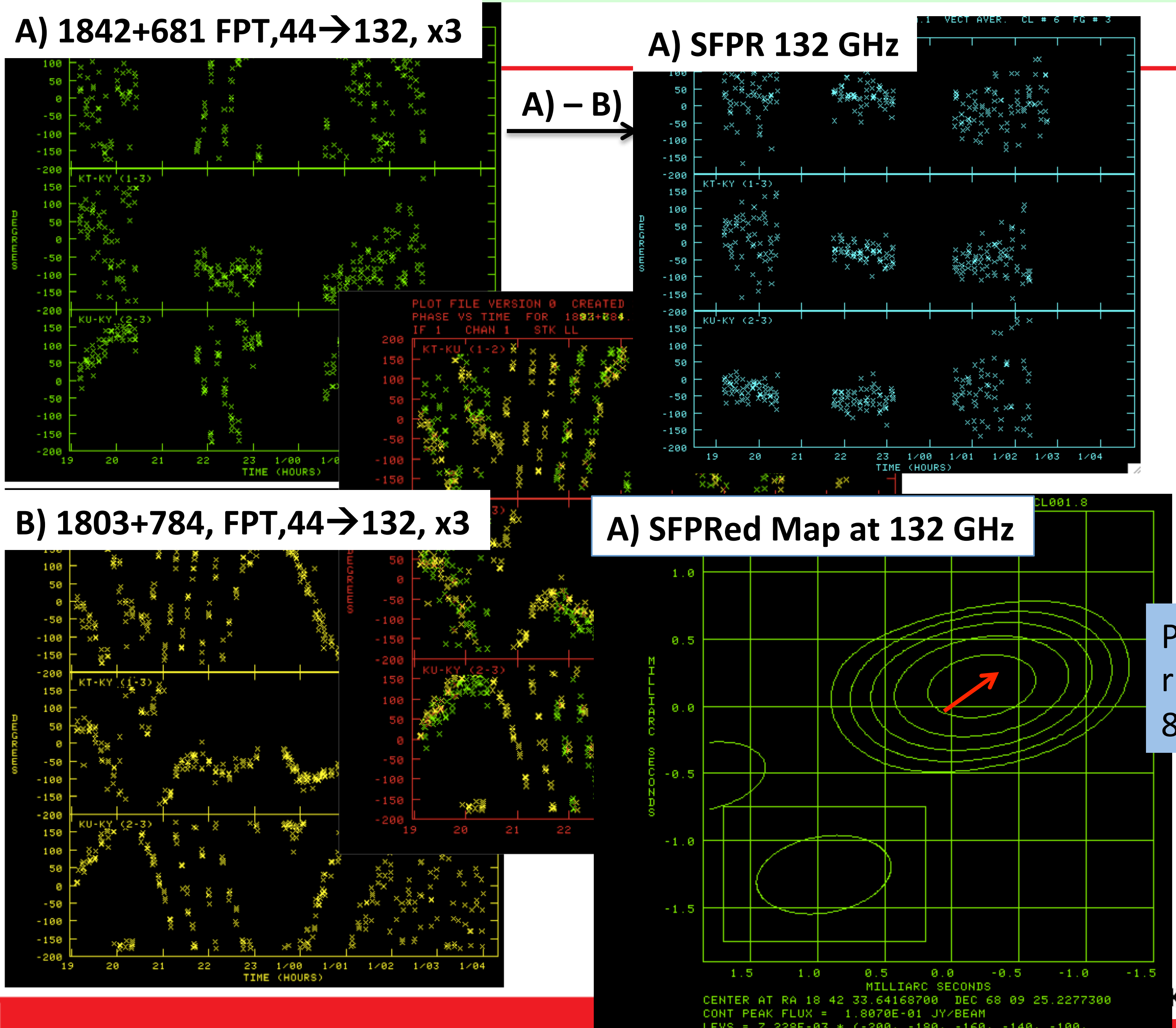
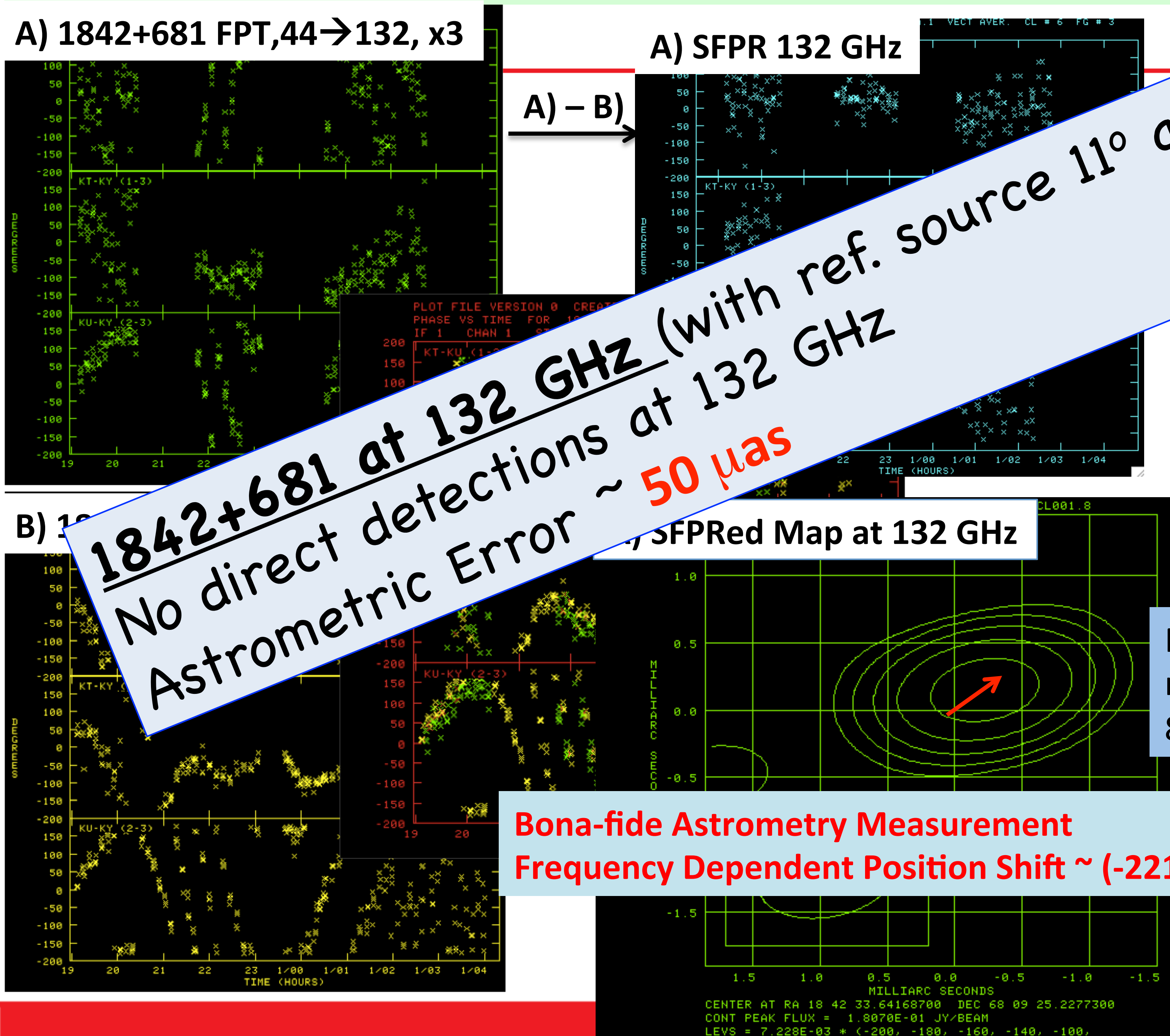
SFPR analysis – 132 GHz with 43GHz: 1842+681 (ref. 11° away)



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

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



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

No direct detections at 132 GHz

Astrometric Error ~ **50 μas**

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

Bona-fide Astrometry Measurement

Frequency Dependent Position Shift ~ (-221,+150) μas

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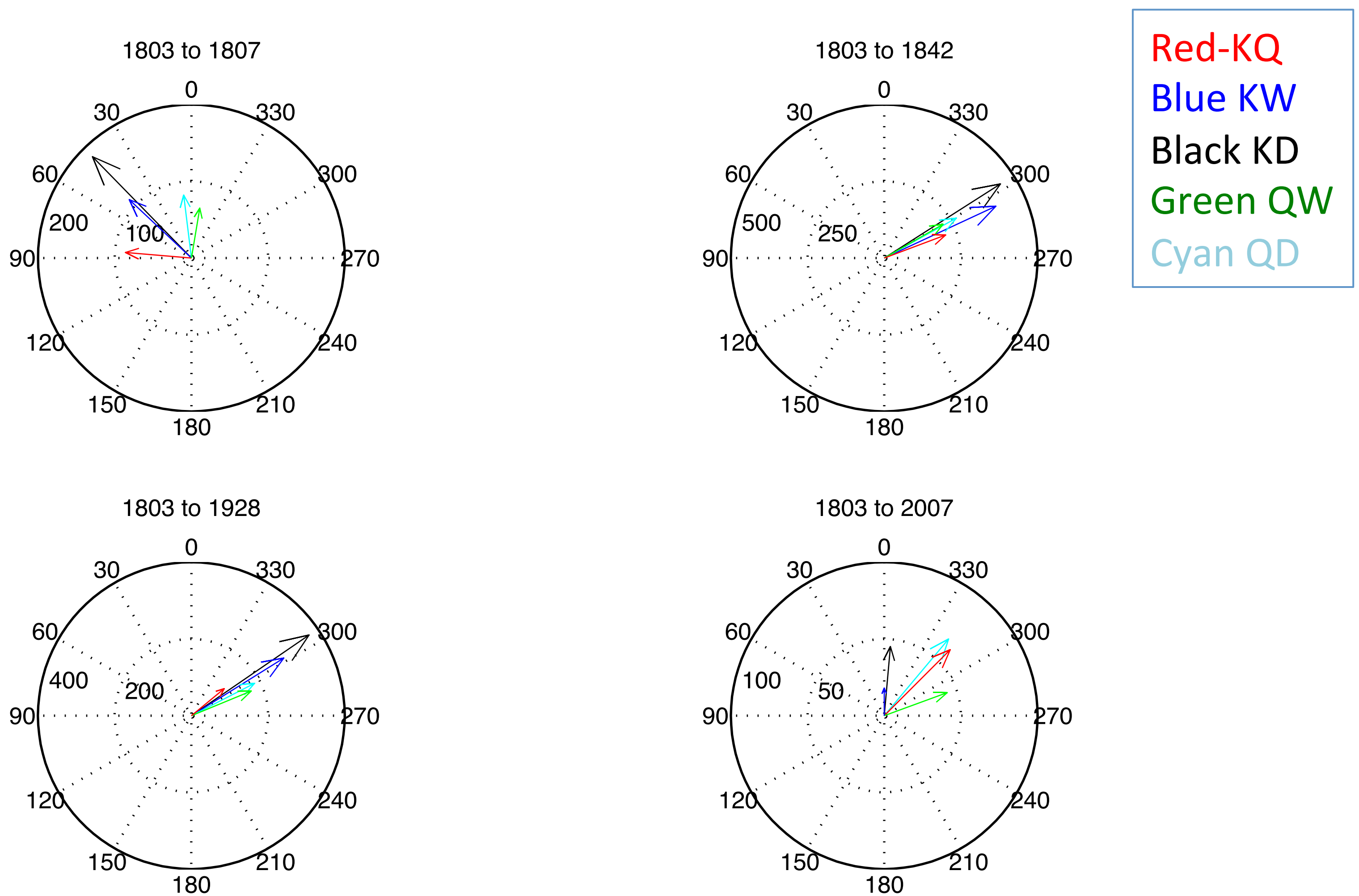
SFPR Astrometric RELATIVE Measurements: between TWO frequencies & TWO sources

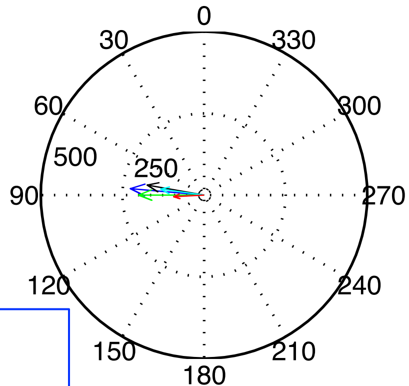


Individual Source Shifts: Singular Value Decomposition Method PLUS Alignment with Jet Direction Constraint

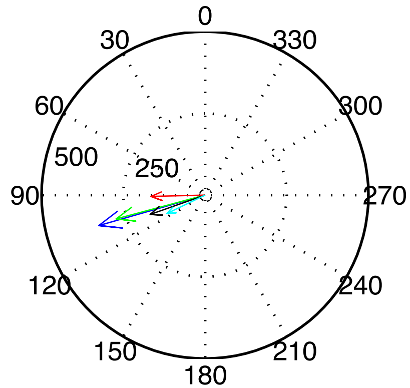
Non-Degenerate Solution

Red KQ
Blue KW
Cyan KD
Green QW
Black QD

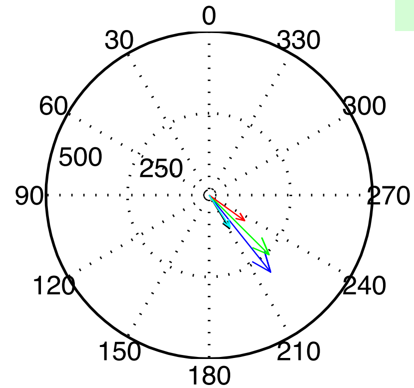
1803+784



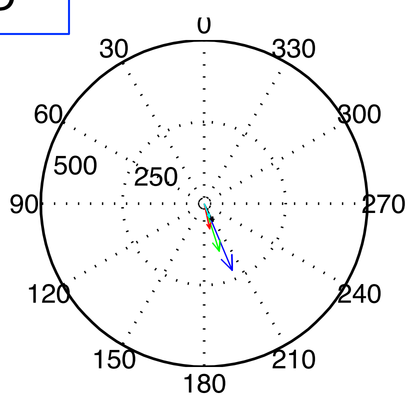
1807+698



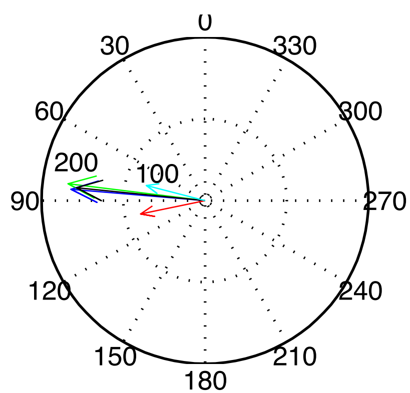
1842+681



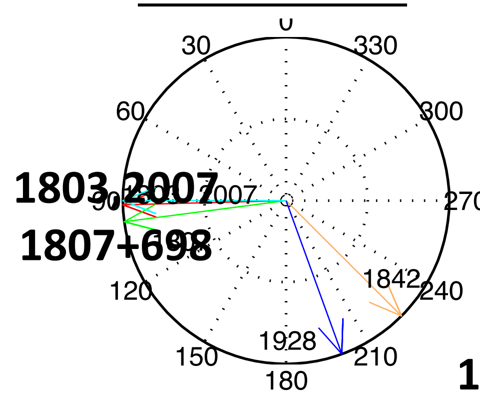
1928+738



2007+777



Jet Directions

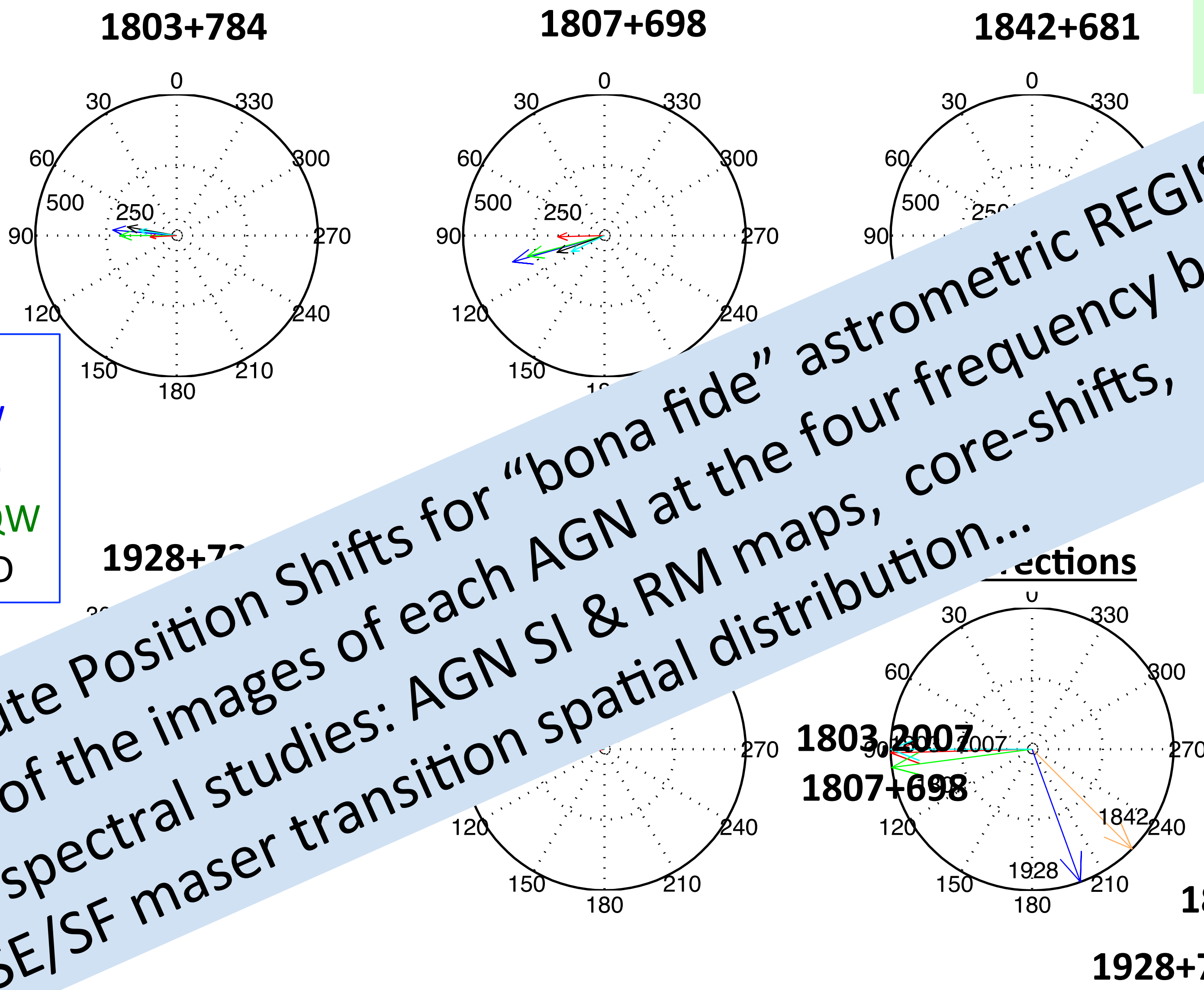


1842+681

1928+738

Individual Source Shifts: Singular Value Decomposition Method PLUS Alignment with Jet Direction Constraint

Non-Degenerate Solution



Red KQ
Blue KW
Cyan KD
Green QW
Black QD

Absolute Position Shifts for “bona fide” astrometric REGISTRATION of the images of each AGN at the four frequency bands.

For spectral studies: AGN SI & RM maps, core-shifts, CSE/SF maser transition spatial distribution…

Empirical 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"

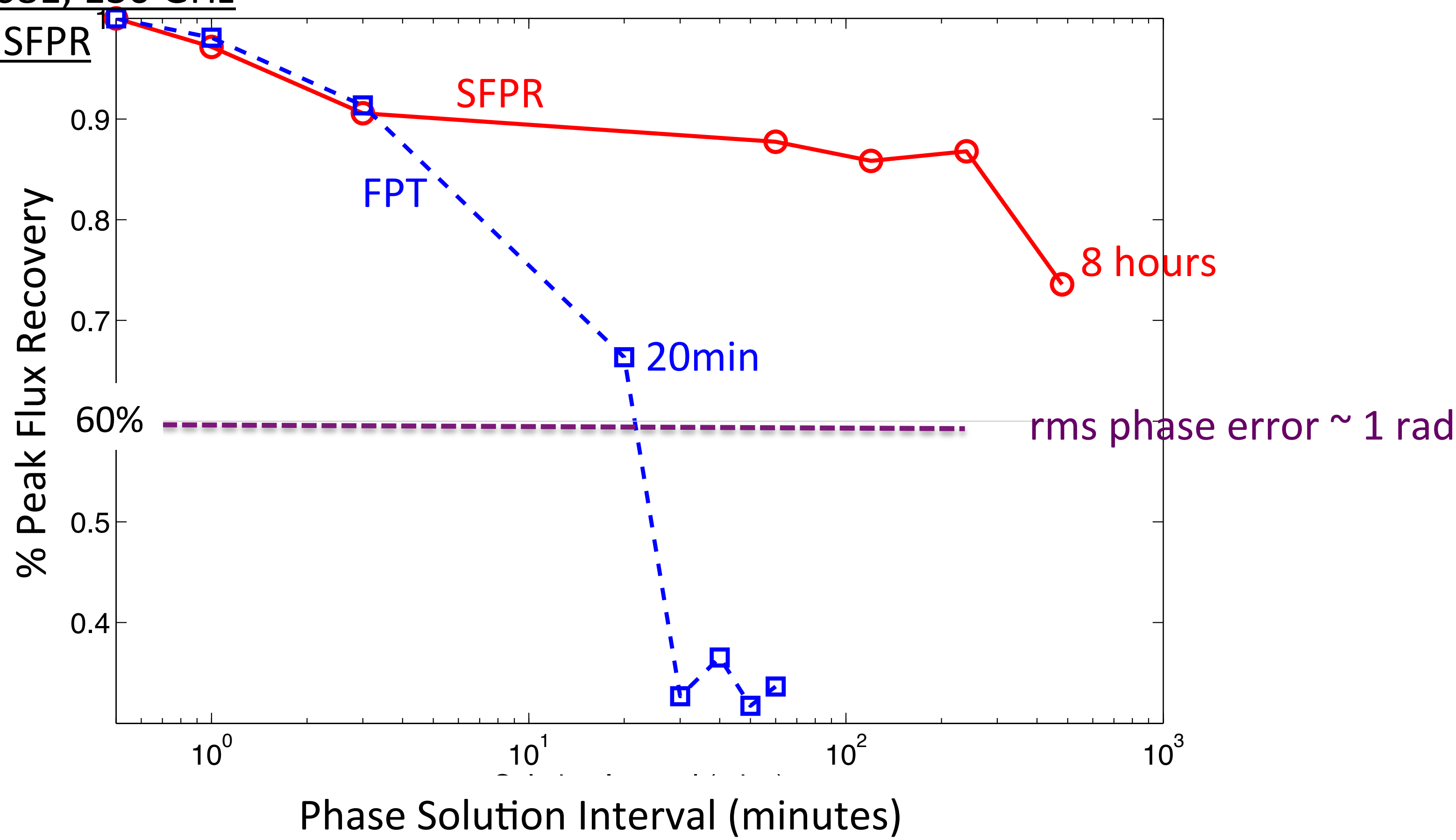
(3) Outcomes: Increased Coherence Time

FPT & SFPR analysis

Empirical Demonstration: Coherence Studies at 130 GHz

Dataset: 1842+681, 130 GHz

Analysis: FPT & SFPR

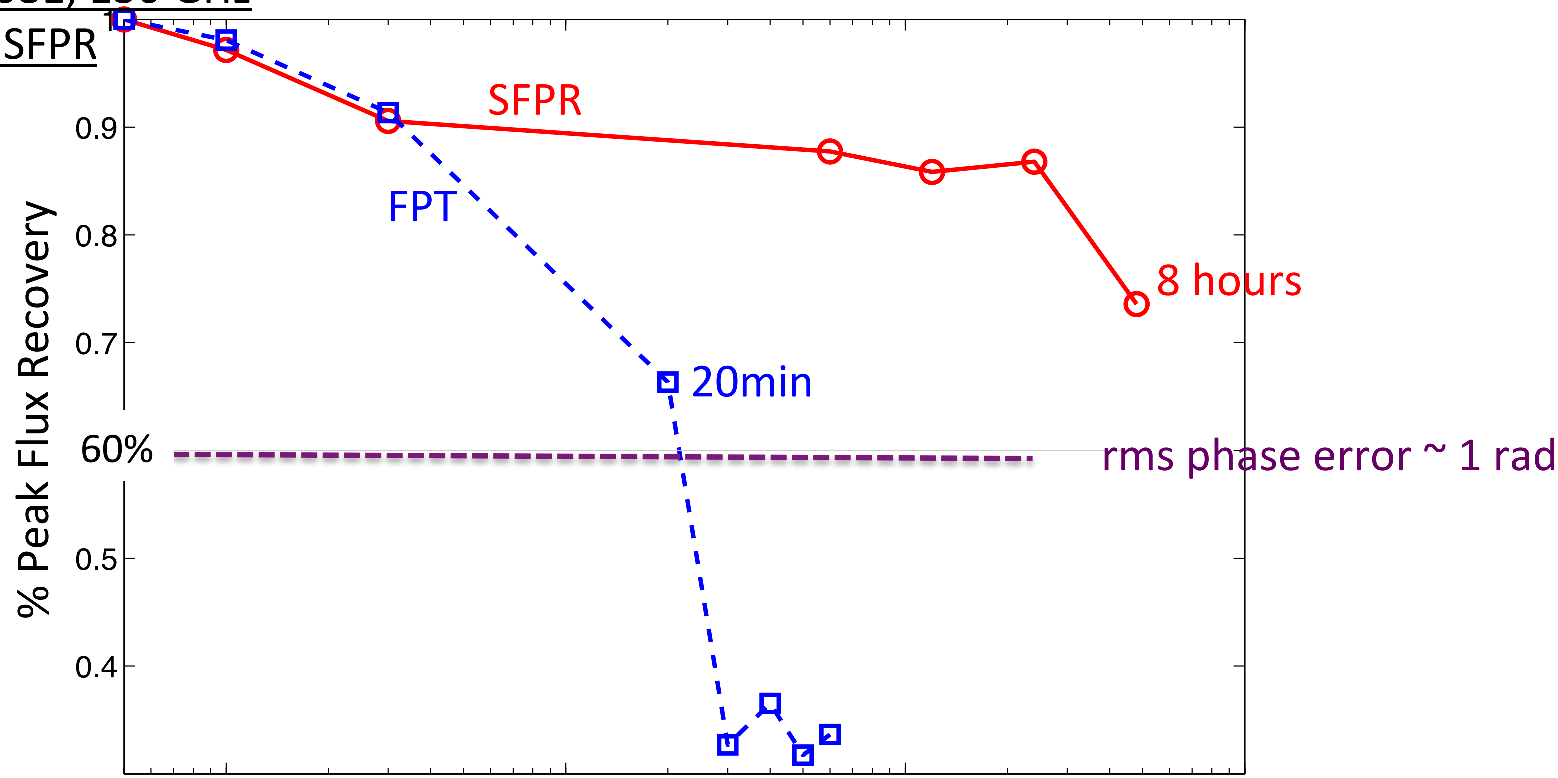


Freq.Pair	Analysis		Effective Coherence Time
44→ 132 GHz	FPT		20 minutes
44→ 132 GHz	SFPR	(θ~11deg)	> 8 hours

Empirical Demonstration: Coherence Studies at 130 GHz

Dataset: 1842+681, 130 GHz

Analysis: FPT & SFPR



Typical Atmospheric Coherence Time @ 130 GHz ~ tens of seconds

Freq.Pair	Analysis	Effective Coherence Time
44→ 132 GHz	**FPT**	**20 minutes**
44→ 132 GHz	**SFPR (θ~11deg)**	**> 8 hours**

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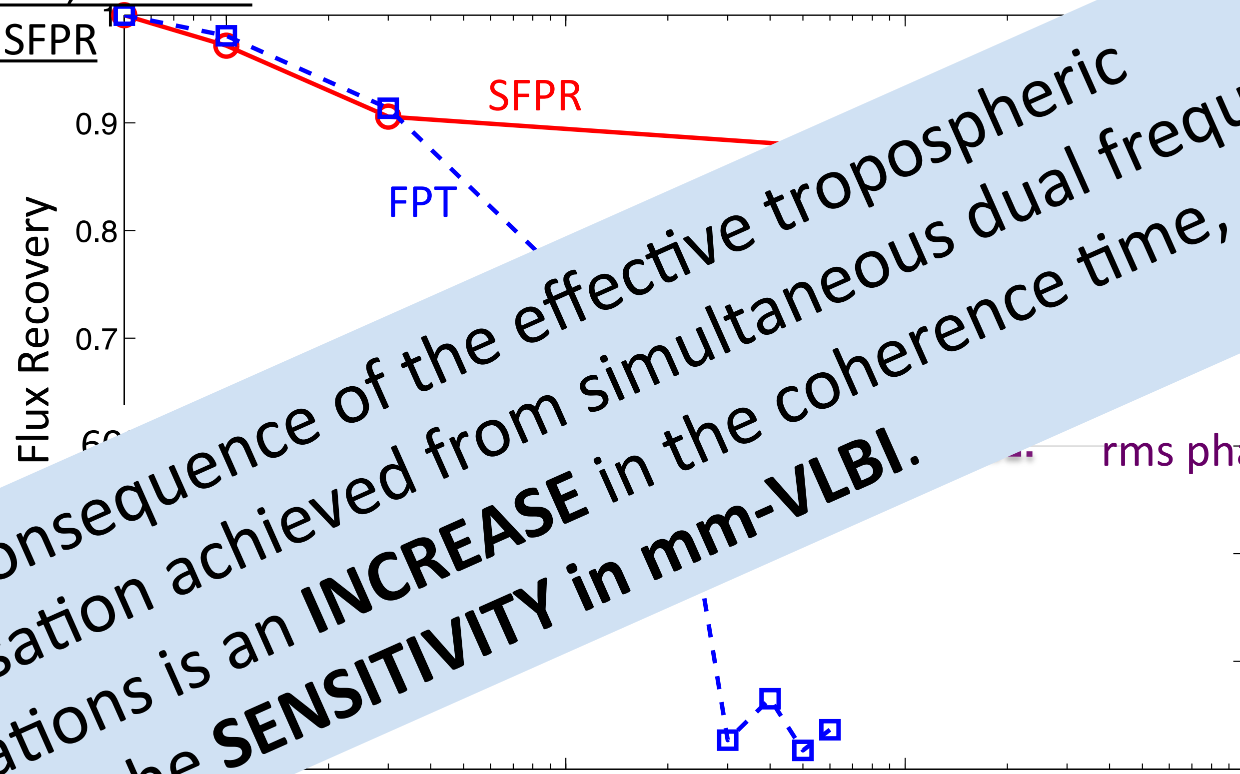
Empirical Demonstration: Coherence Studies at 130 GHz

Dataset: 1842+681, 130 GHz

Analysis: FPT & SFPR



A direct consequence of the effective tropospheric compensation achieved from simultaneous dual frequency observations is an **INCREASE** in the coherence time, and therefore the **SENSITIVITY in mm-VLBI**.

T… pheric Coherence Time @ 130 GHz ~ tens of seconds

eq.Pair	Analysis	Effective Coherence Time
44→ 132 GHz	FPT	20 minutes
44→ 132 GHz	SFPR (θ~11deg)	> 8 hours

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Summary

Potential of multi-frequency observations to improve the performance of mm-VLBI

SFPR enables:

- **Superior tropospheric compensation, boost array with increased sensitivity.**
- **High precision astrometry at (sub-)mm-VLBI**
- **No upper frequency limit (B2B mode in ALMA at ca. 650 GHz)**

Widely applicable, to many sources
Very effective use of observing time
Technology ready, Slow telescope switching

Empirical Demonstration with KVN observations up to 132 GHz:
First time astrometric measurements made at 130 GHz
Coherence time extended to 20 minutes (FPT) or greater than 8 hours (SFPR)

Astrophysical applications:

- Multi-frequency **studies with "bona fide" astrometric registration, in continuum and spectral line observations.**
- **Weak Sources**

Work in Progress – What's next?

Network: **International Baselines (KVN Pilot Project) (Tuesday morning)**
(long baselines highly desirable for increased astrometric precision, resolution

Engineering: Possibilities for (near) simultaneous multi-frequency obs.
(mid Tuesday)

Analysis: ICE Blocks for ionospheric calibration (alternative to SFPR)
(today)

Unique Science Drivers (today):
AGNs, Evolved Stars / Star forming regions, weak sources.
KVN applications to spectral line studies

Leading to General discussions with a forum of engineers and astronomers
"How to establish a European Multi-Frequency Observatory"
(end Tuesday)

END