International
Centre for
Radio
Astronomy
Research

Astrometry at Highest Frequencies

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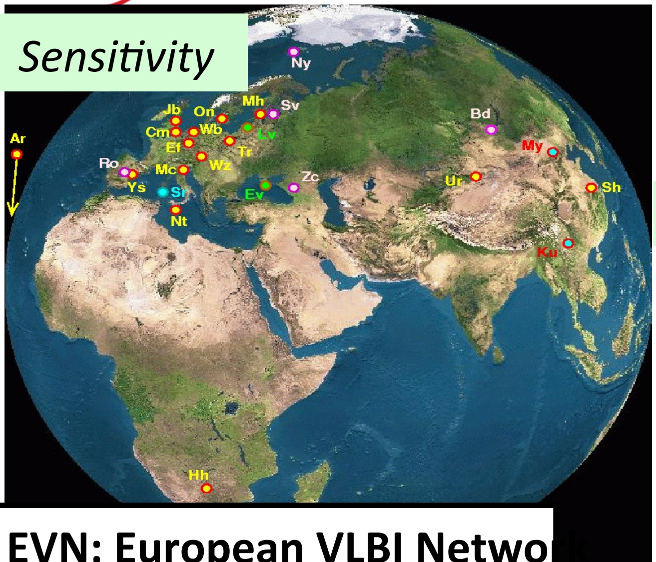
THE UNIVERSITY OF WESTERN AUSTRALIA

Outline

- Difficulties of astrometry at High Frequencies
- Impact of multi-channel receivers of KVN on astrometric Studies using Source Frequency Phase Referencing (SFPR)
- Examples of SFPR observations (VLBA @ 86 GHz; KVN vs VLBA @ 44 GHz; KVN @ 132 GHz)
- Conclusions

VLBI NETWORKS

Sensitivity



EVN: European VLBI Network

<~ 22GHz

General Purpose

VLBA Very Long Baseline Array

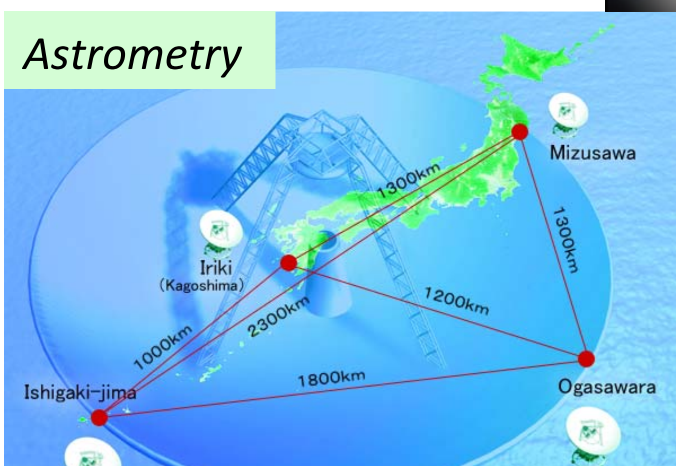
<~ 86GHz

Highest Frequency Astrometry

KVN Korean VLBI Network

22/43/86/129 GHz

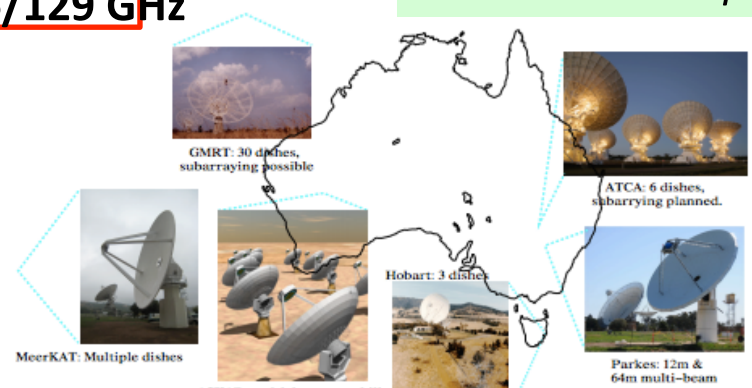
Astrometry



VERA VLBI for Earth Rotation and Astrometry

22/43 GHz

Southern Hemisphere



LBA Long Baseline Array

<~ 22GHz

and Space Science Institute

VLBI NETWORKS

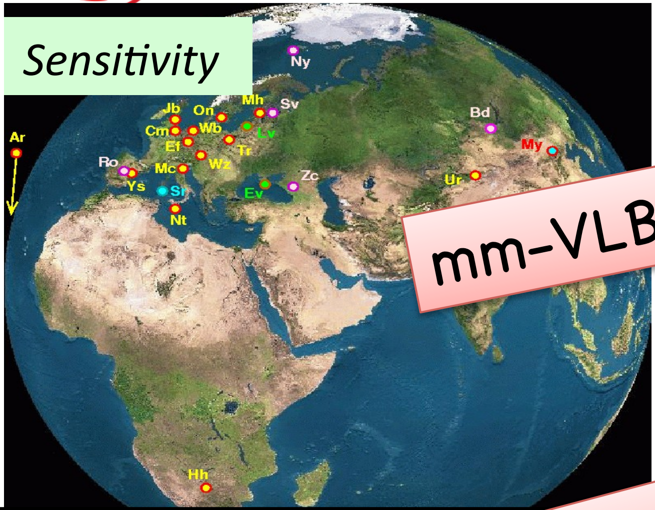
λ / D

mm-VLBI is very interesting!

Why mm-VLBI is difficult?

Innovative solution implemented in KVN to do it

Sensitivity



EVN: European VLBI Net

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General Purpose

Very Long Baseline Array

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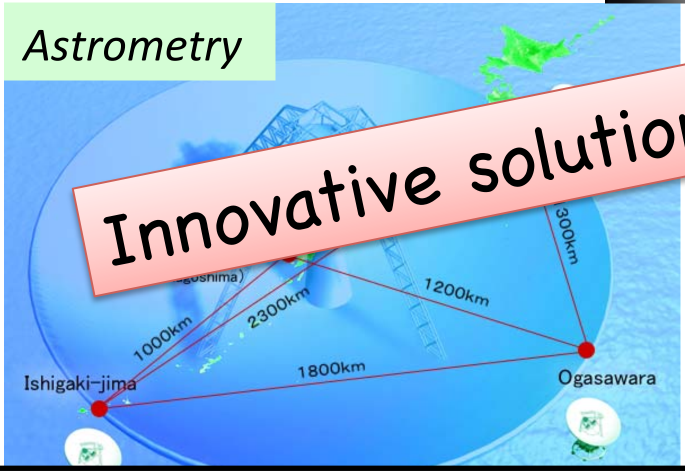
...st Frequency Astrometry

KVN Ko...

Astrometry



VERA VLBI for Earth Rotation and Astrometry

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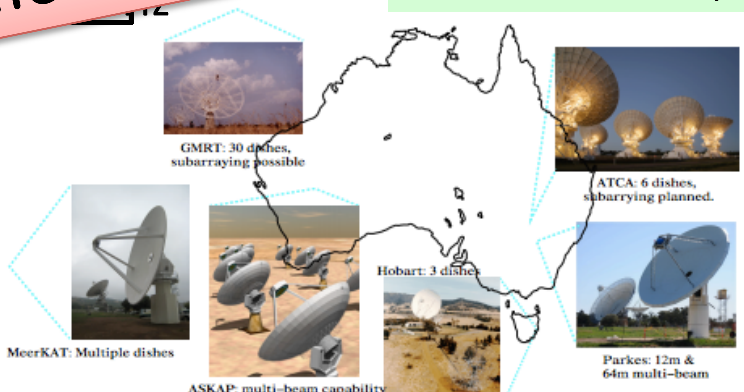

LBA Long Baseline Array

<~ 22GHz

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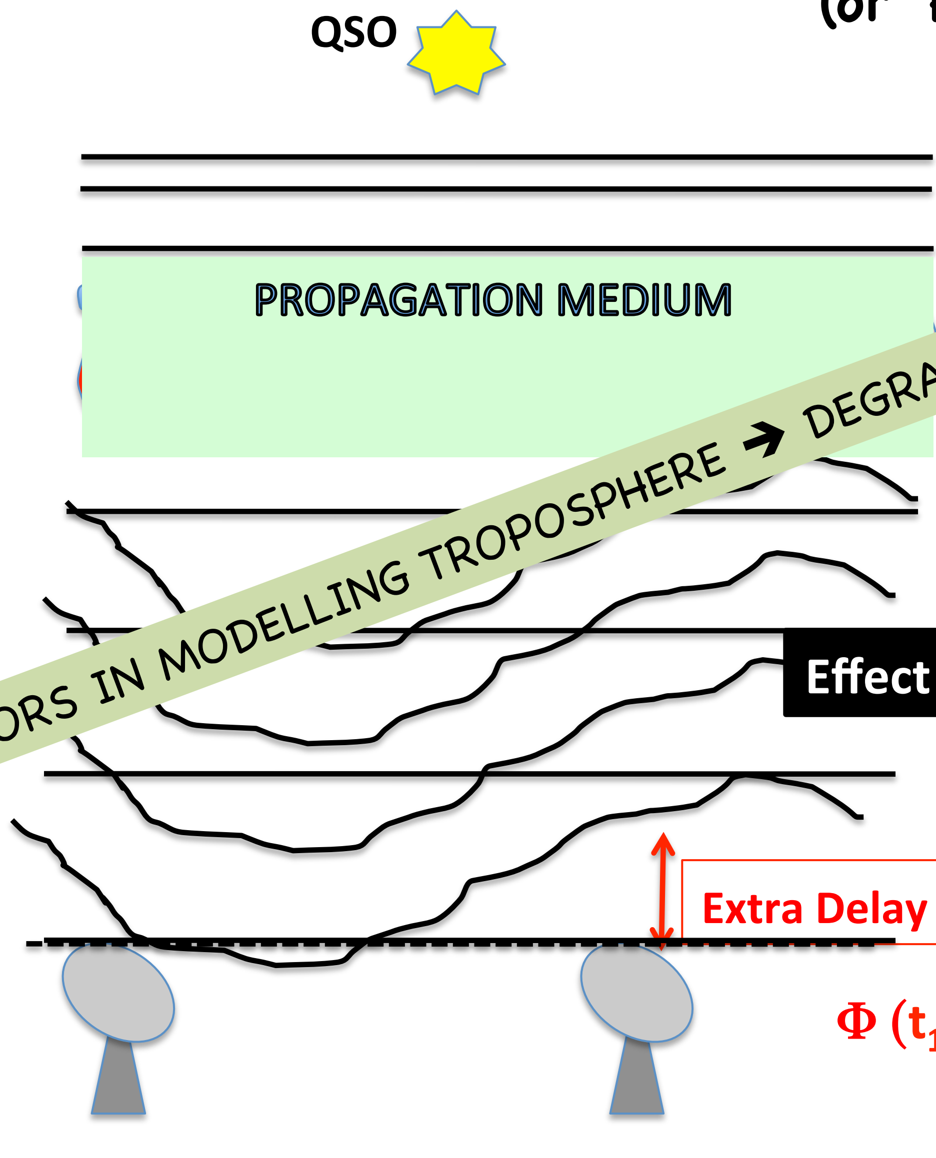
PHASE STABILITY – ATMOSPHERE

(or "Phase Differences Fluctuations")



Incoming wavefront….

Wavefront a… …osphere

…patial Structure

… after atmospheric Distortion

Effect amplified at higher frequencies

"Phase" changing with time

Extra Delay (τ) => Extra Phase (Φ)

$\Phi\,(t_1) = 2\,\pi\,\nu\,\tau$

ERRORS IN MODELLING TROPOSPHERE → DEGRADATION OF ASTROMETRIC ACCURACY

ALTERNATIVE TROPOSPHERIC CALIBRATION IN MM-VLBI

Conventional PR: to a calibrator source

(requirements difficult to meet)

fast

43 ➡ 43 GHz

Different source

Dual-frequency PR: to a lower frequency

NEW

- **Observe at lower band (e.g. 21.5 GHz)**
- **Apply (scaled) to higher band (e.g. 43 GHz)**

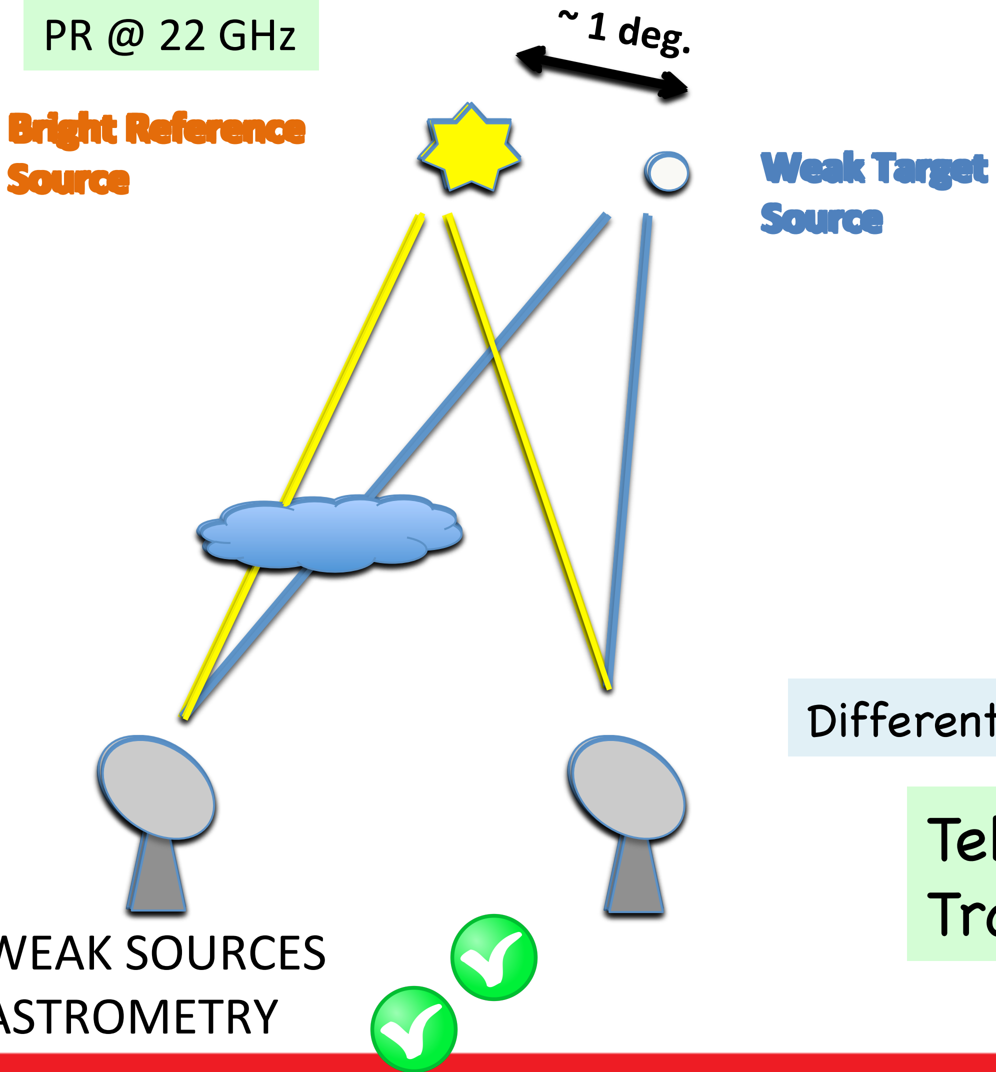
⬆ fast

Same source

(Rioja & Dodson+, 2009, 2011, 2012, 2014)

ASTROMETRY with Phase Referencing

PR @ 22 GHz



AIM: Isolate geometric signature in interferometric phase

STRATEGY:

Use analysis of interleaving observations of reference source as a GUIDANCE to calibrate out PROPAGATION MEDIUM contributions in target observations.

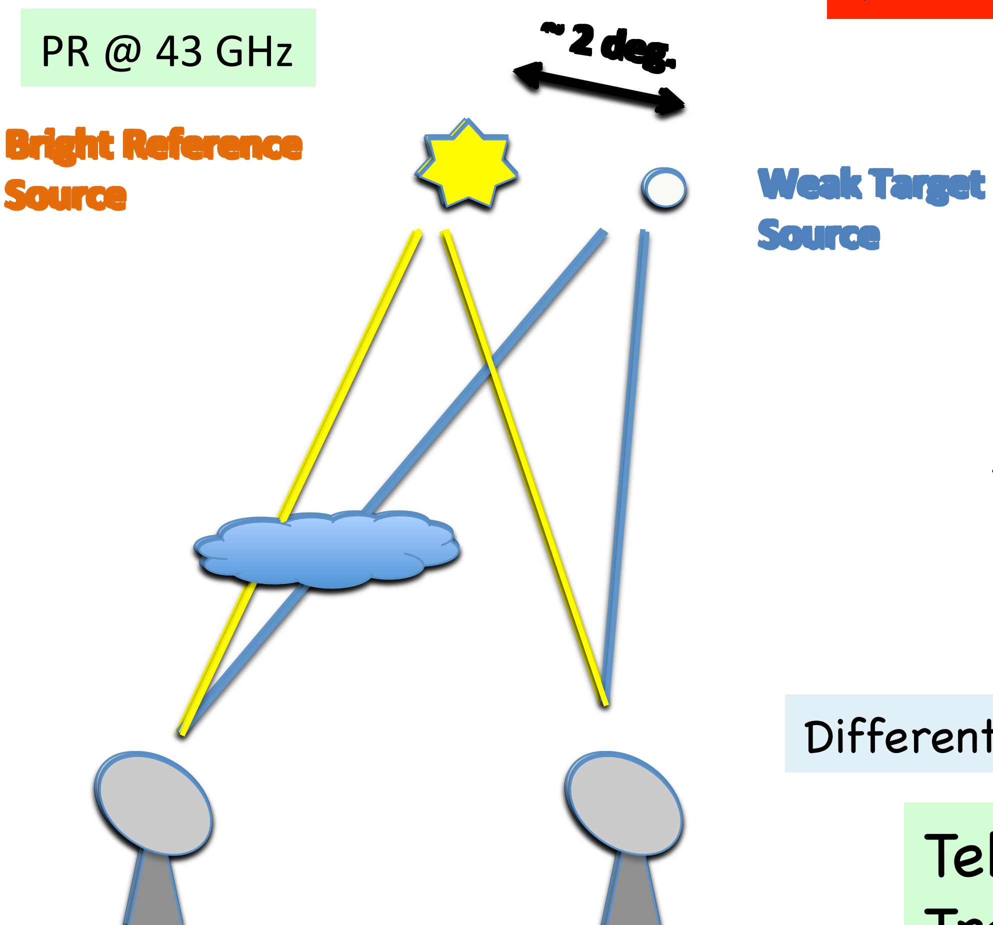
Different observing times, different line-of-sight

Telescope Switching matches Tropospheric coherence time.

WEAK SOURCES ASTROMETRY

ASTROMETRY with Phase Referencing

43 GHz is the Upperbound frequency for PR



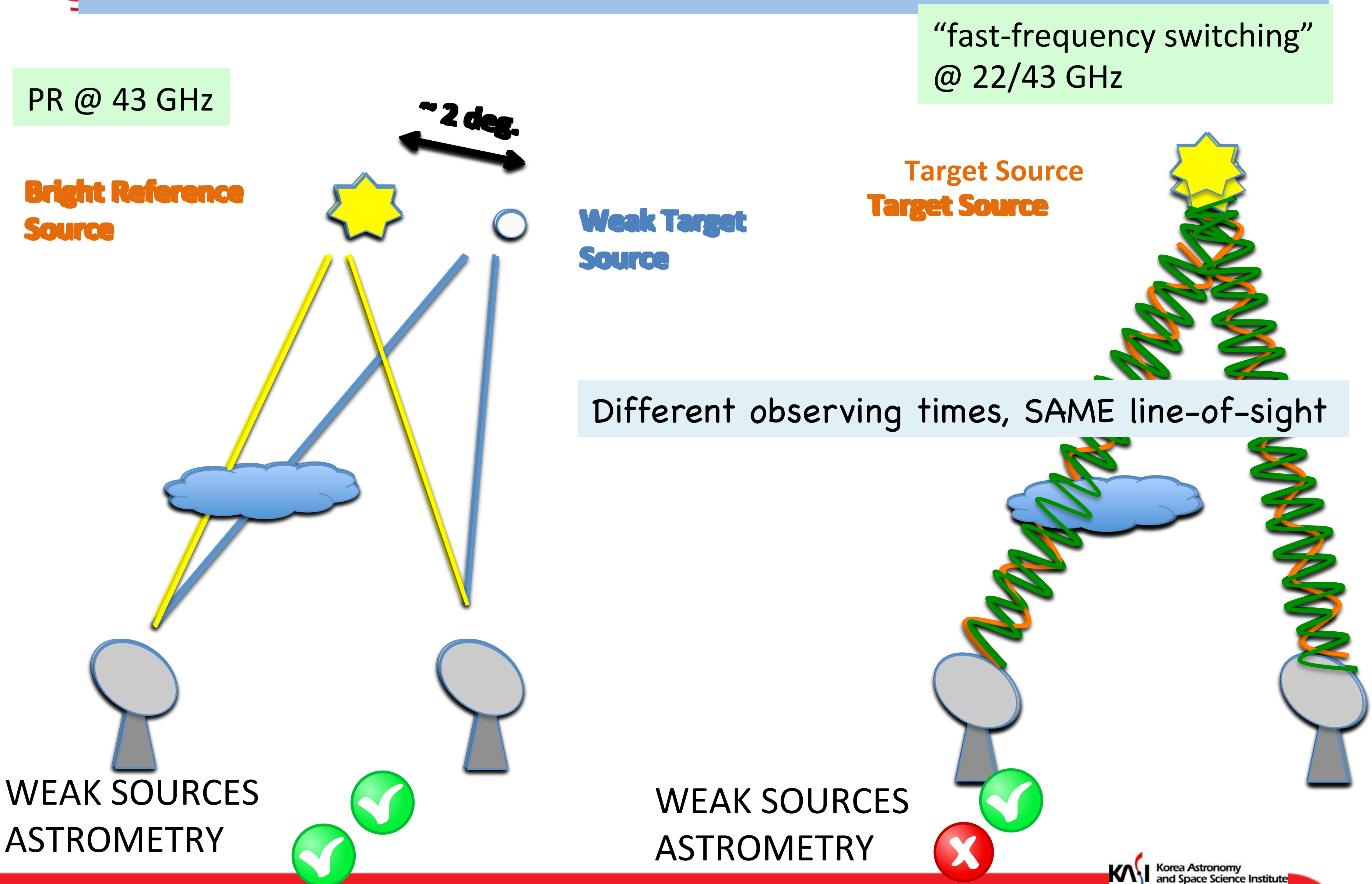
In VERA observations, with Dual-beam, there is the calibrator Issue.

Different observing times, different line-of-sight

Telescope Switching matches Tropospheric coherence time.

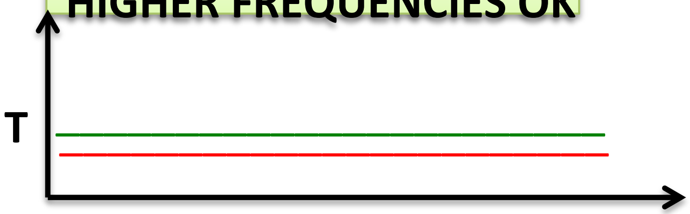
WEAK SOURCES ASTROMETRY

ALTERNATIVE APPROACH FOR TROPOSPHERIC (non-dispersive) COMPENSATION

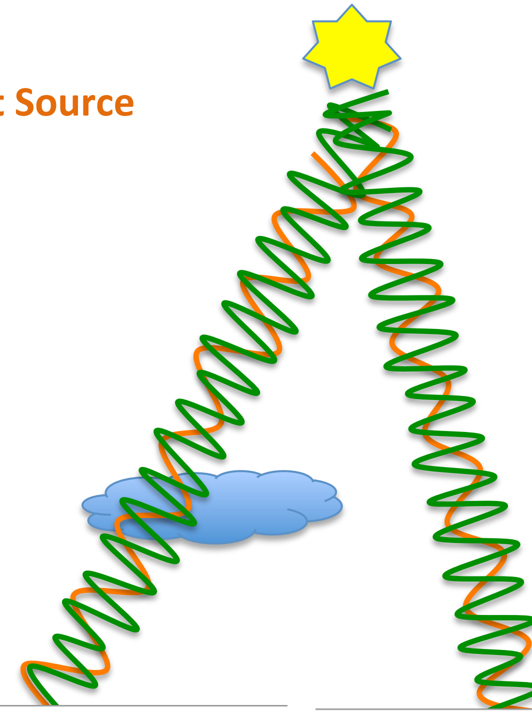


ALTERNATIVE APPROACH FOR TROPOSPHERIC (non-dispersive) COMPENSATION

BETTER SIMULTANEOUS!
HIGHER FREQUENCIES OK



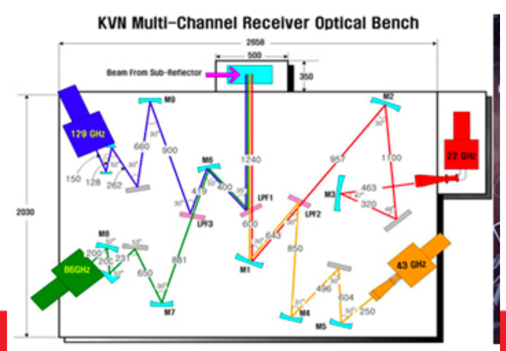
Target Source

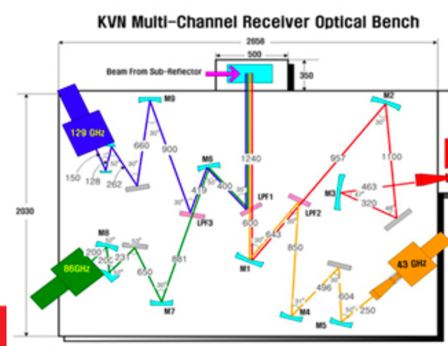


SAME observing times, SAME line-of-sight

Superior Tropospheric Calibration!

Multi-Channel KVN receivers

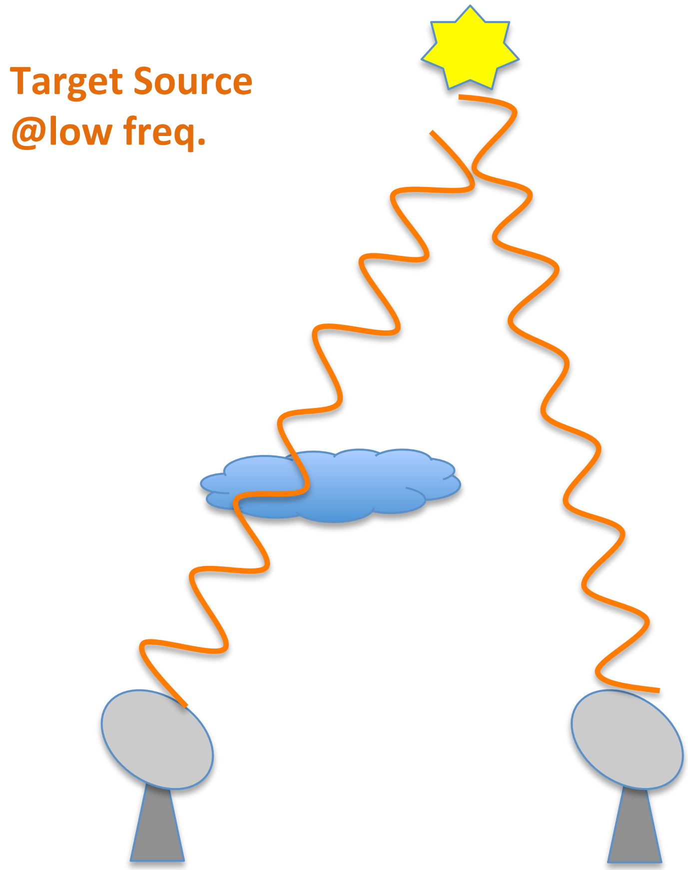




WEAK SOURCES ✓
ASTROMETRY ✗

The quest for astrometry: 1st step: Frequency Phase Referencing (FPT)

(TWO FREQUENCIES, ONE SOURCE)

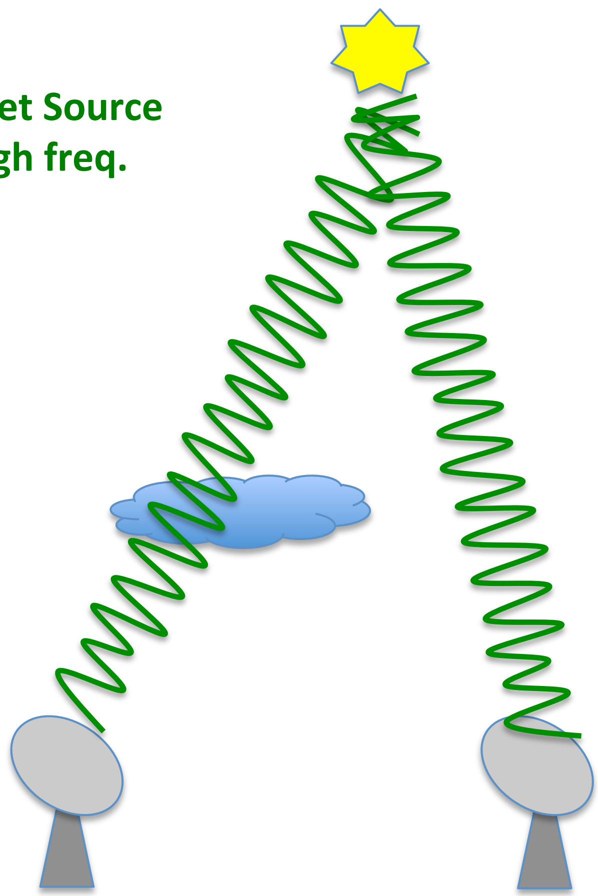


$$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A$$

The quest for astrometry: 1st step: Frequency Phase Referencing (FPT)

(TWO FREQUENCIES, ONE SOURCE)

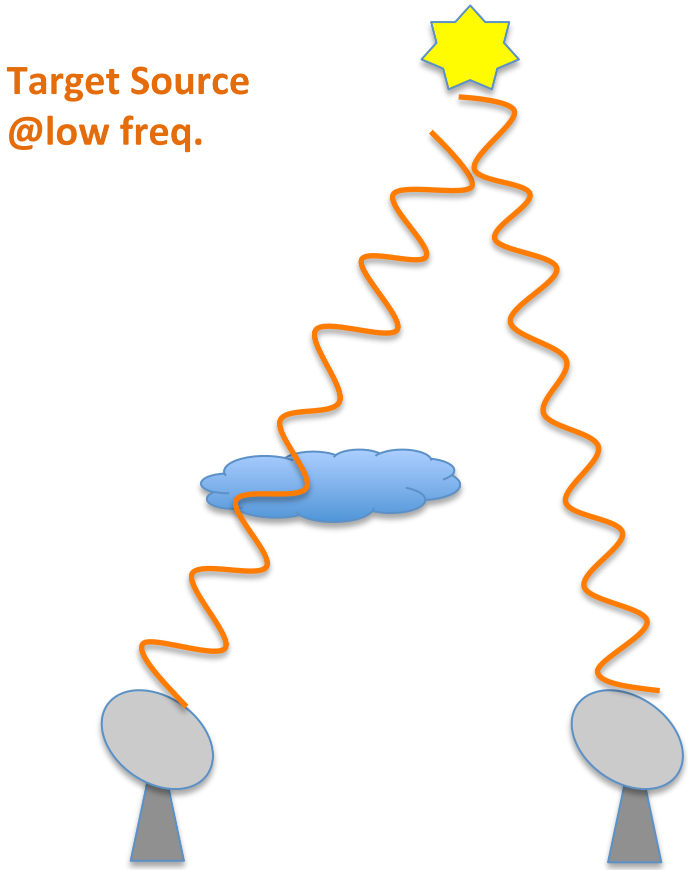
Target Source @high freq.



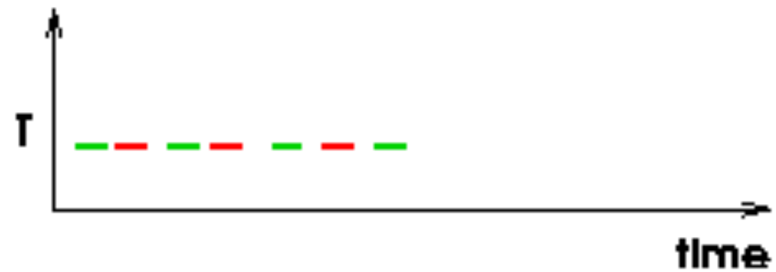
$$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + \phi_{A,STR} + 2\pi n_A$$

The quest for astrometry: 1st step: Frequency Phase Referencing (FPT)

(TWO FREQUENCIES, ONE SOURCE)



If Fast-Freq-Switching
Temporal Interpolation ONLY
<u>NOTE:</u> No Spatial interpolation!!!!!



<u>VERY IMPORTANT</u>:

1) Duty Cycle Matches temporal scale of Instabilities, for successful temporal interpolation.

If Simultaneous Observatons:
NO Interpolation → NO errors
<u>BETTER ASTROMETRY!</u>

The quest for astrometry: 1st step: Frequency Phase Referencing (FPT)

BETTER SIMULTANEOUS!
HIGHER FREQUENCIES O…

NO Interpolation →
BETTER ASTROMETRY!

Target Source
@low&high freq.

INCREASED COHERENCE TIME, BUT NO ASTROMETRY

$R = \nu / \nu$, **integer**

Fast

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

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

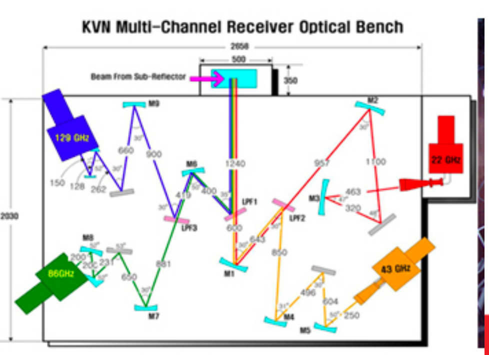
Non-dispersive Errors:

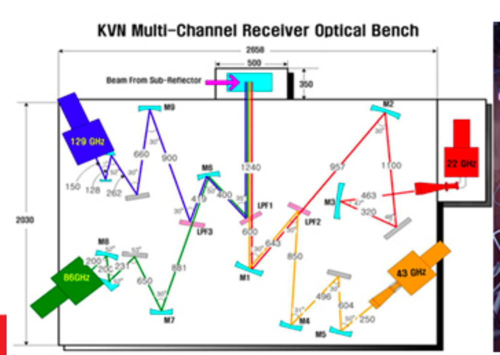
$\phi_{A,TRO} - R * \phi_{A,TRO} = 0$

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

Dispersive Errors:

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





KVN

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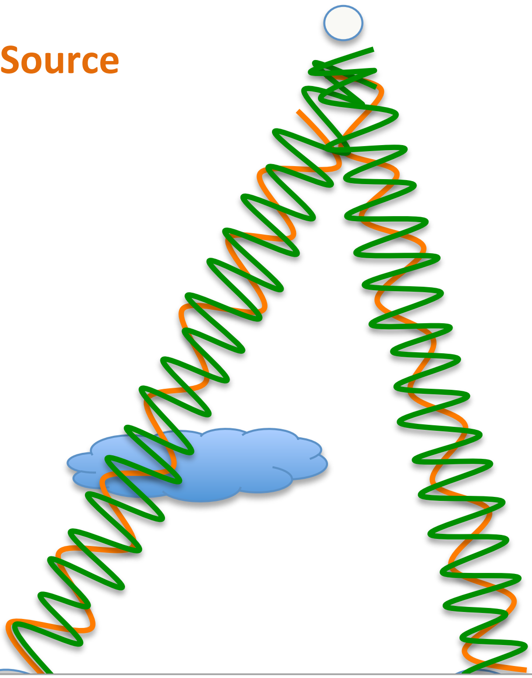
2nd step: ASTROMETRY with Source-Frequency-Phase-Referencing *(SFPR)*

(2 frequencies, 2 sources)

SFPR: Rioja & Dodson 2008,2011

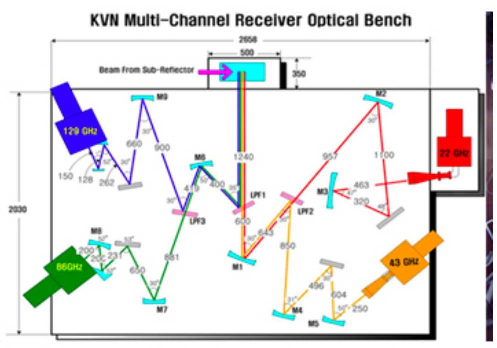
WEAK SOURCES ✓

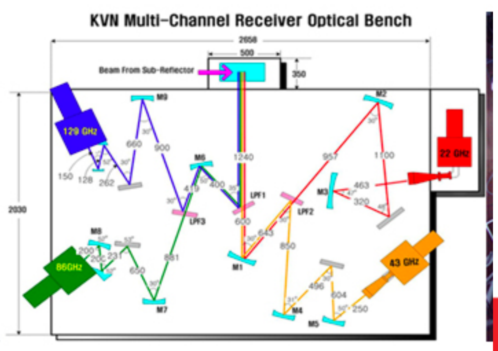
ASTROMETRY ✓



Fast Slow Slow

$\phi_A = \phi$ ✗ $O + \phi$ ✗ $O + \phi_{A,ION} + \phi_{A,INST} + \phi_{A,STR} + 2\pi n_A$



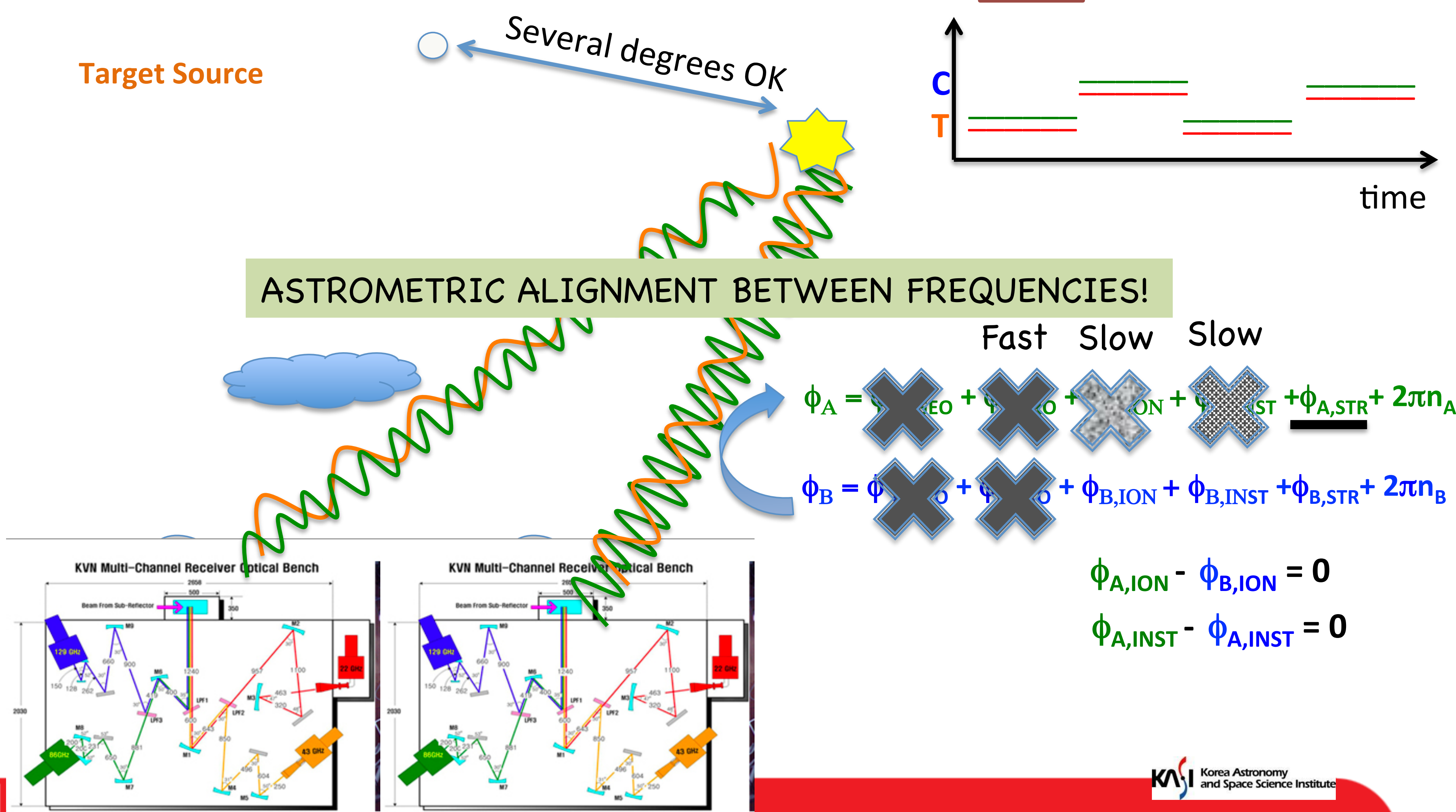


2nd step: ASTROMETRY with Source-Frequency-Phase-Referencing *(SFPR)*

(2 frequencies, 2 sources)

WEAK SOURCES

ASTROMETRY



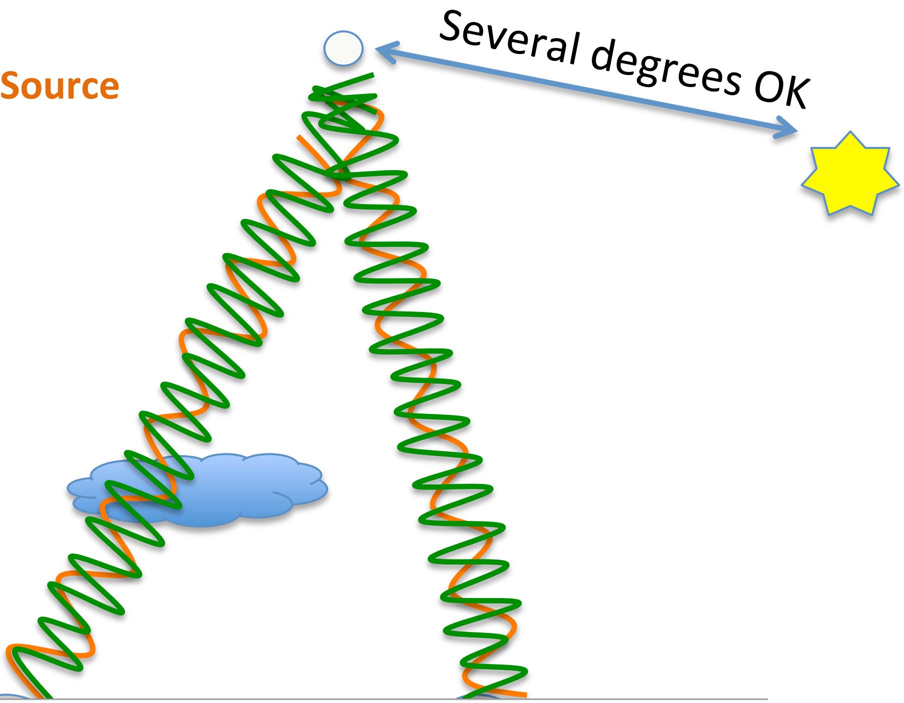
2nd step: **ASTROMETRY** with Source-Frequency-Phase-Referencing *(SFPR)*

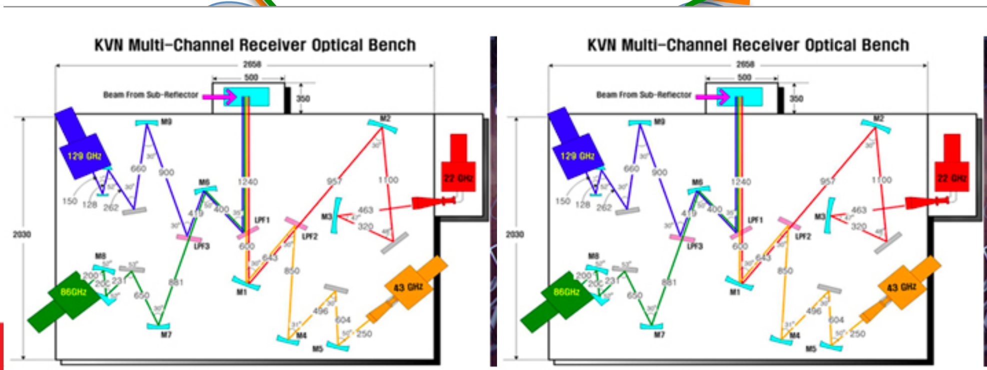
(2 frequencies, 2 sources)

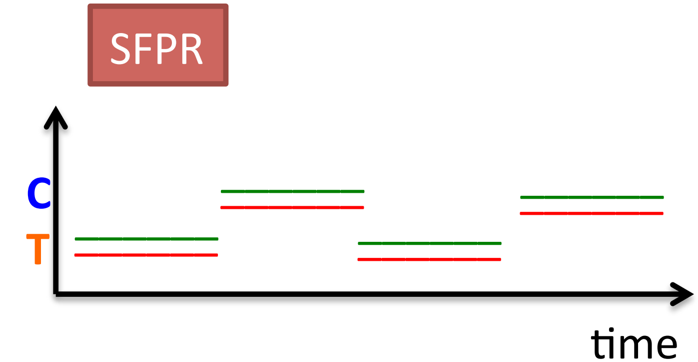
WEAK SOURCES ✔

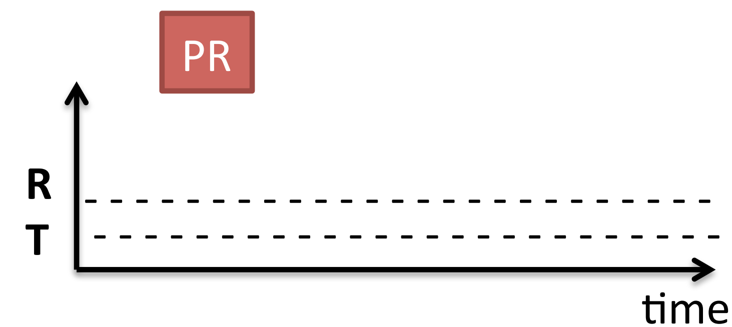
ASTROMETRY ✔

Target Source



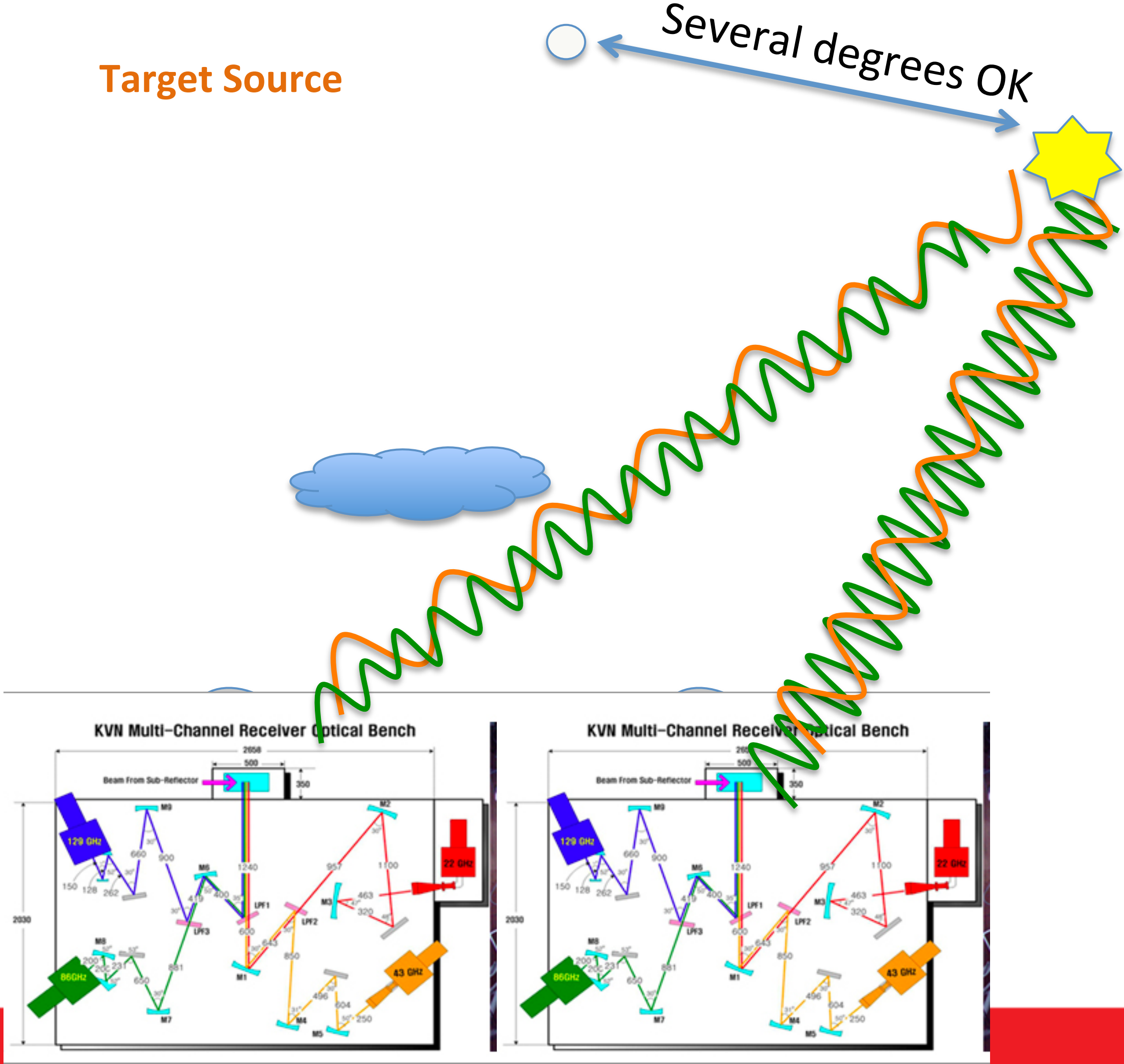


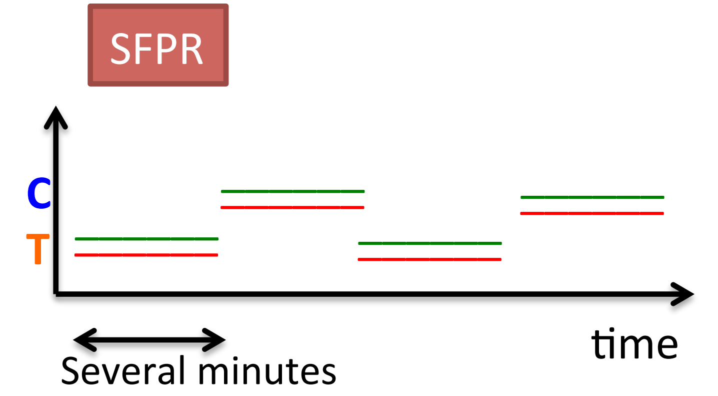




2nd step: ASTROMETRY with Source-Frequency-Phase-Referencing *(SFPR)*
(2 frequencies, 2 sources)

WEAK SOURCES
ASTROMETRY

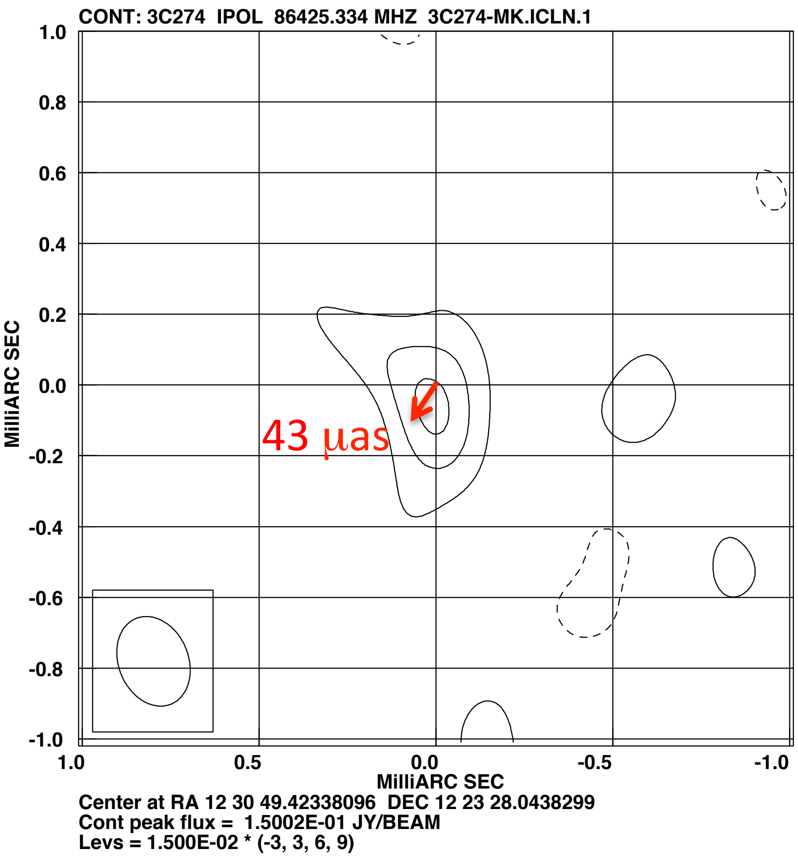




Examples of SFPR measurements

M87: Core-Shift Measurement between 43 and 86 GHz

Obs. 2007, M87 wrt. 3c273, 10^{o} apart, VLBA SFPR



VLBA
Fast Frequency Switching (Duty cycle 1min)
Between 43/86 GHz

SFPR-ed map:
First empirical demonstration.

Flux Recovery ~ 30%
(Quality of prop. media compensation)

Limit of high frequency for fast freq switching

(Rioja + Dodson, 2011)

OUTCOMES OF SOURCE-FREQUENCY-PHASE-REFERENCING

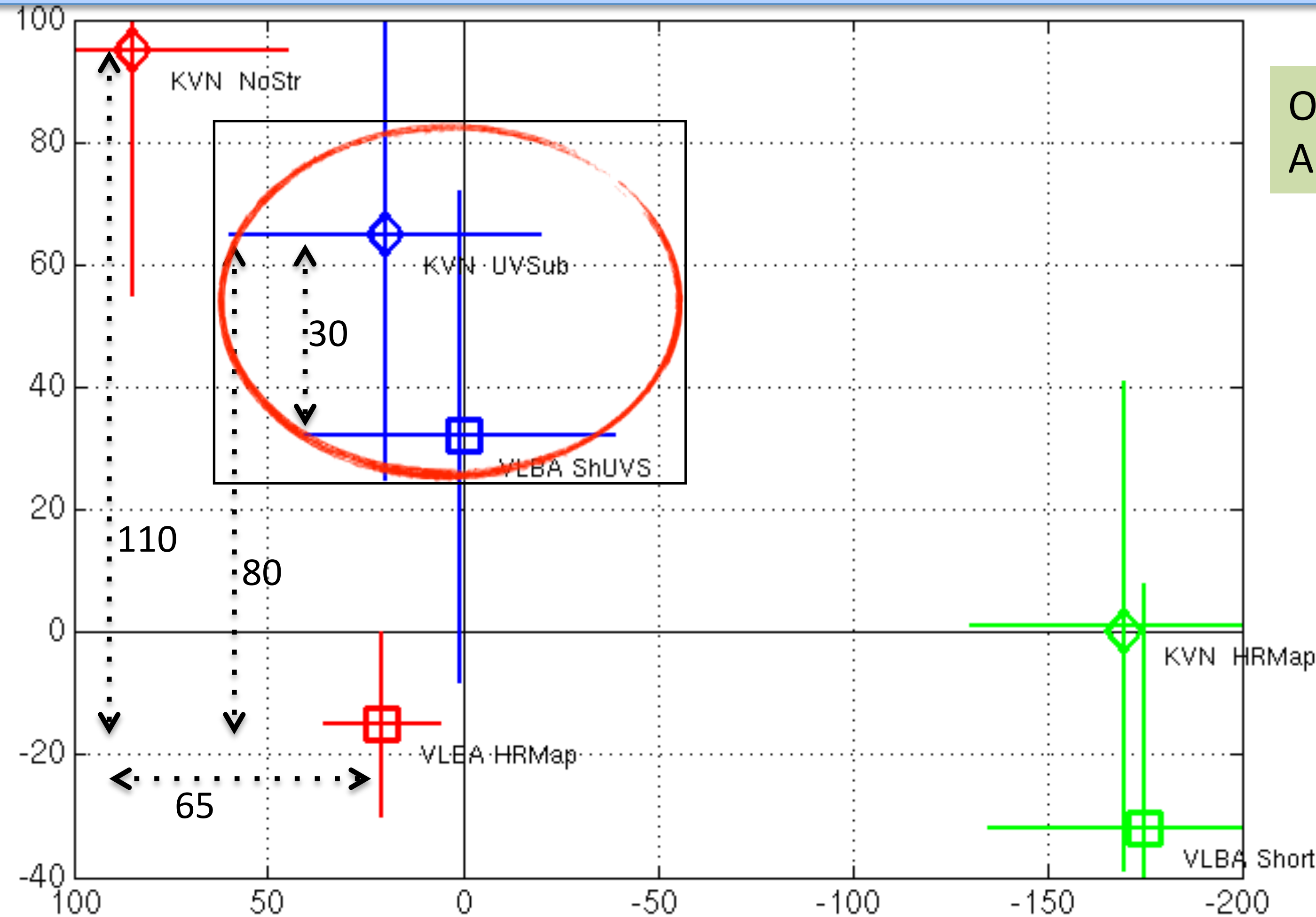
ENABLES, AT HIGH FREQUENCIES:

HIGH PRECISION CHROMATIC ASTROMETRY:
Bona-fide astrometric alignment of multi-frequency images (e.g. *for spectral index studies, core shift, molecular transitions spectral line…*).
Ultimate precision, given by resolution.
&
HIGH SENSITIVITY ➔ **Weak Source** Detection

Slow switching OK
Several Degrees away OK

Examples of SFPR measurements

KVN vs. VLBA : VERIFICATION OF SFPR Astrometric CAPABILITY AT 22/43 GHz



Obs. date
April 2013

VLBA-sh beam: 2.1 x 1.6 mas, PA=58 deg
KVN beam: 3 x 1.5 mas, PA=90deg

(Rioja, Dodson + KVN Team, 2014)

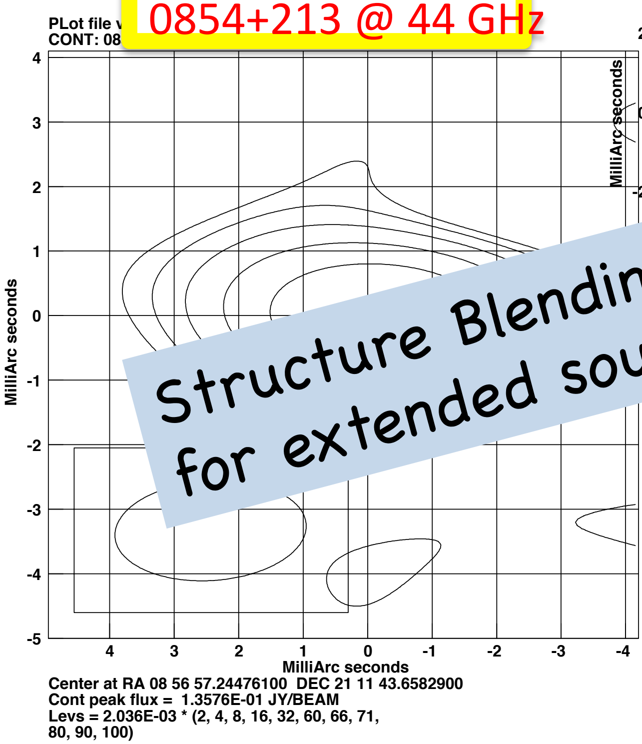
ICRAR

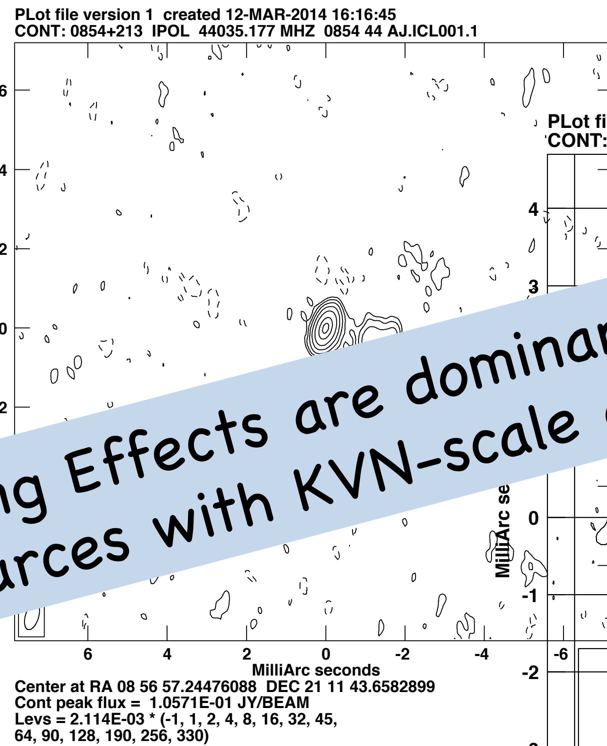
VLBA Hybrid map
0854+213@44GHz

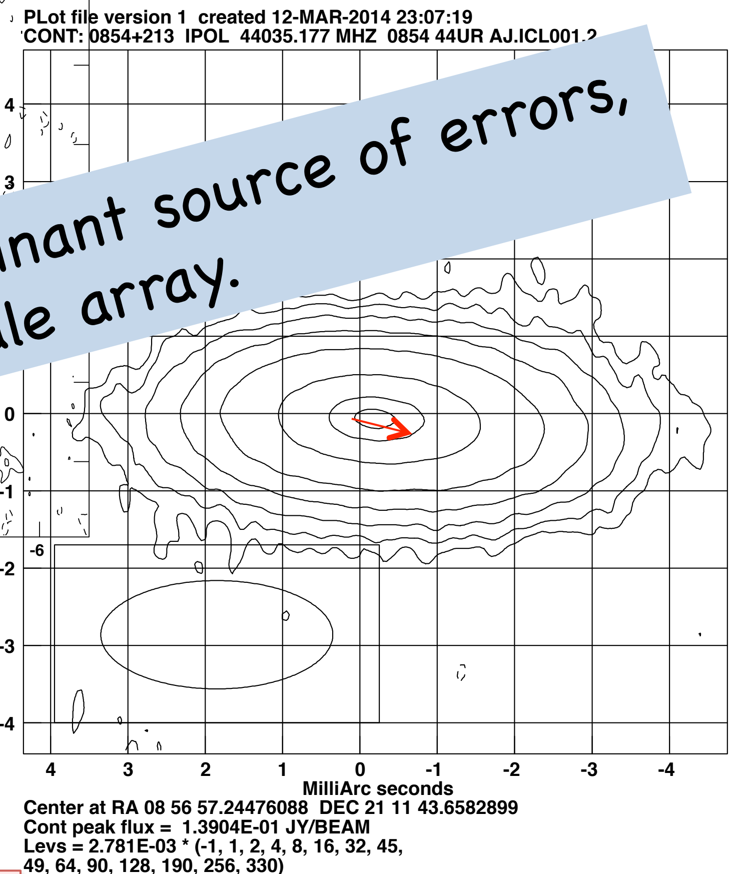
VLBA Hybrid map
0854+213@44GHz
Convolved with KVN beam

KVN SFPR-ed map
0854+213@44GHz

0854+213 @ 44 GHz







Structure Blending Effects are dominant source of errors,
for extended sources with KVN-scale array.

Offset ~ 170 micro-as in both cases

Flux Recovery VLBA 88%; KVN 94%

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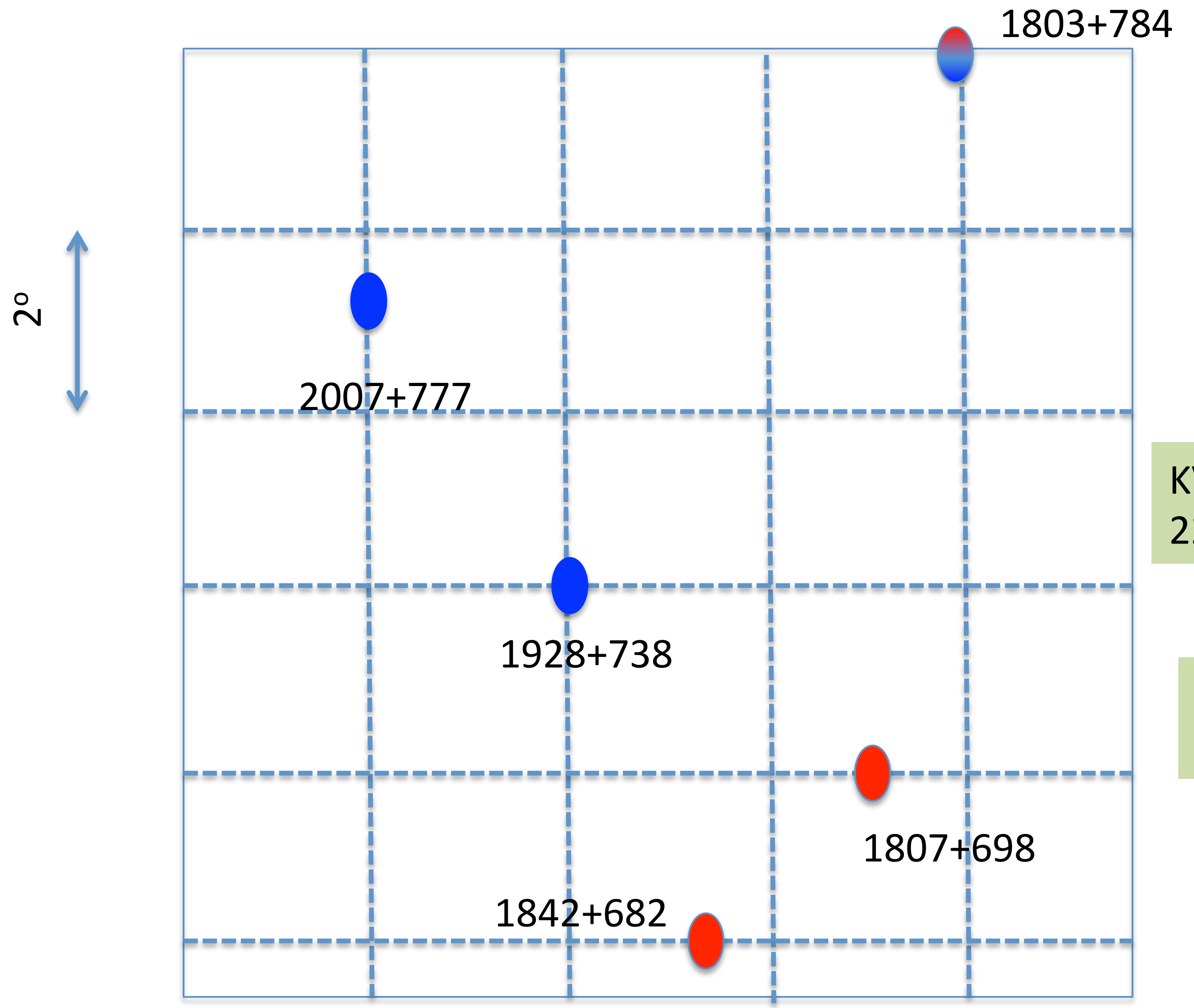
Examples of SFPR measurements

Latest SFPR results on sources from Polar Cap sample with KVN



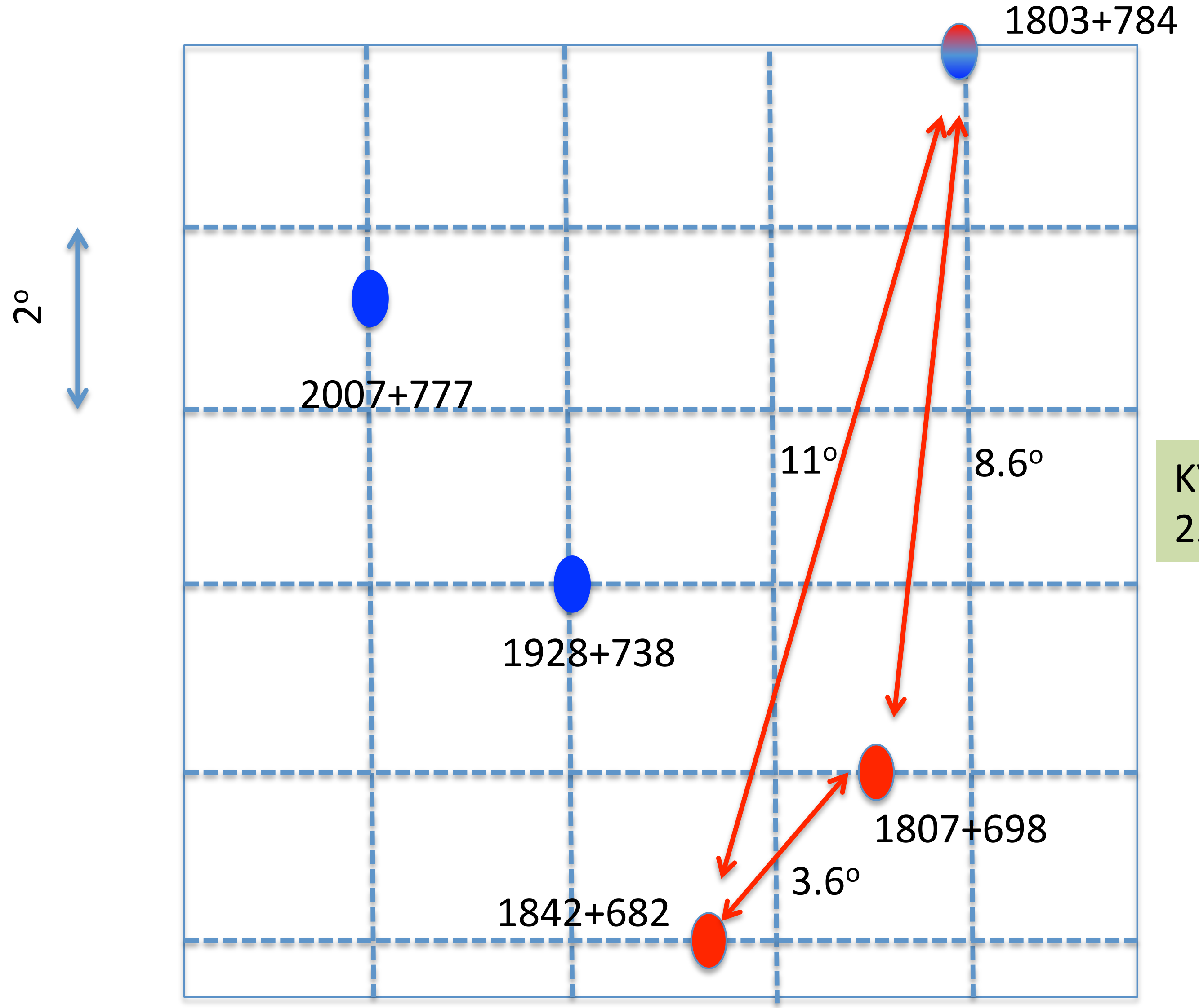
Triangle 1
Triangle 2

KVN full operational:
22,43,86,129 GHz

Obs. date
March 2014

Examples of SFPR measurements

Latest SFPR results on sources from Polar Cap sample with KVN



Triangle 1
Triangle 2

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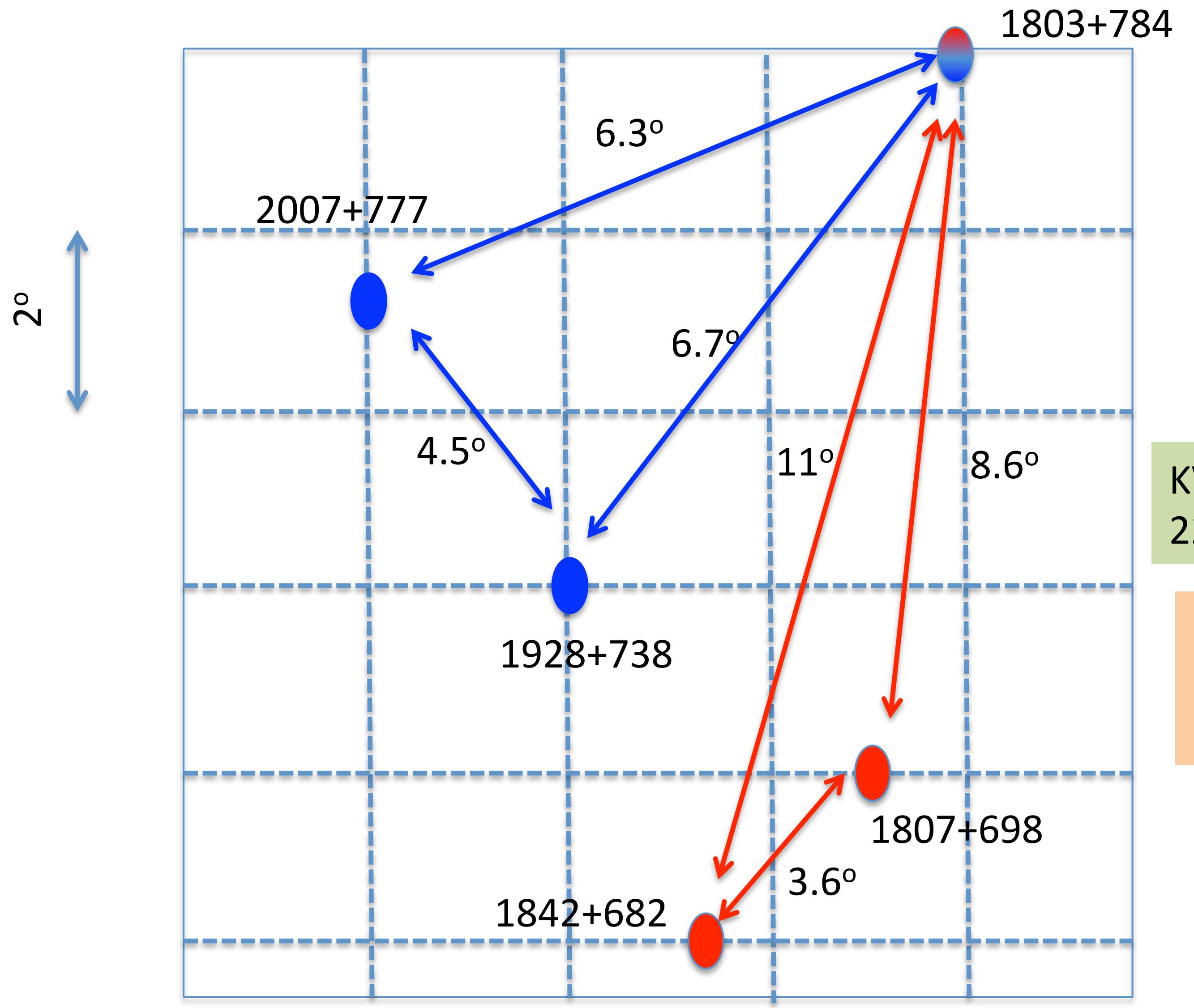
22,43,86,129 GHz

Examples of SFPR measurements

Latest SFPR results on sources from Polar Cap sample with KVN



Triangle 1
Triangle 2

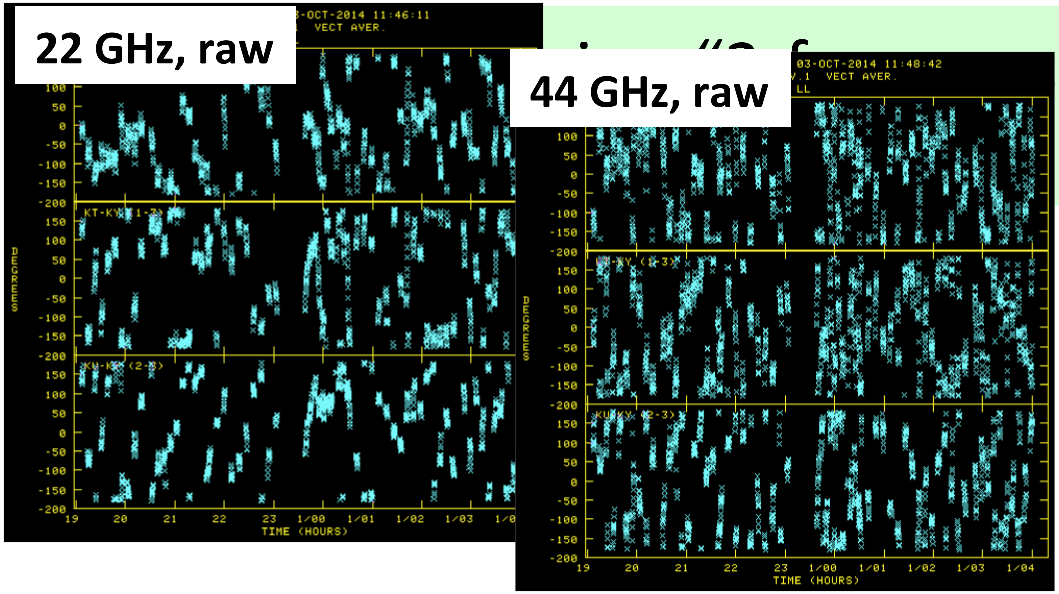
KVN full operational:
22,43,86,129 GHz

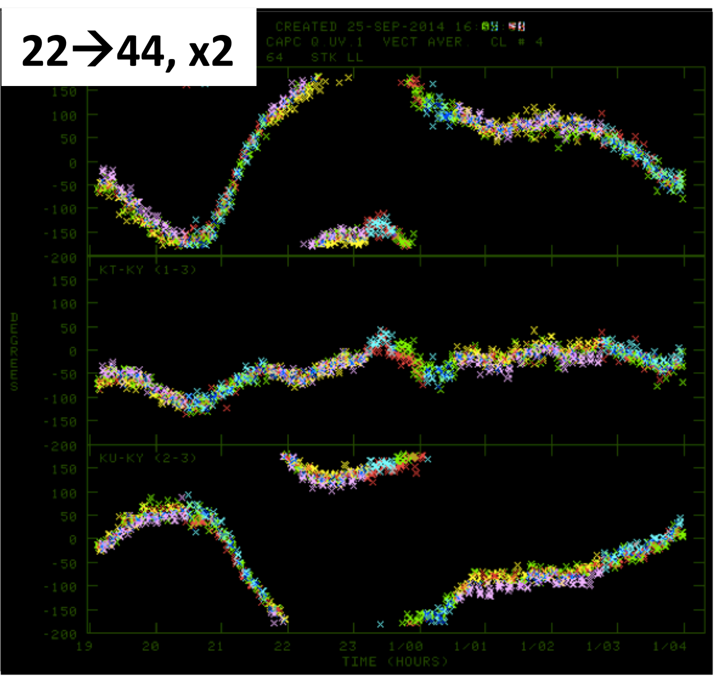
KVN Obs.:
Duration 8 hours
3 min scan/source

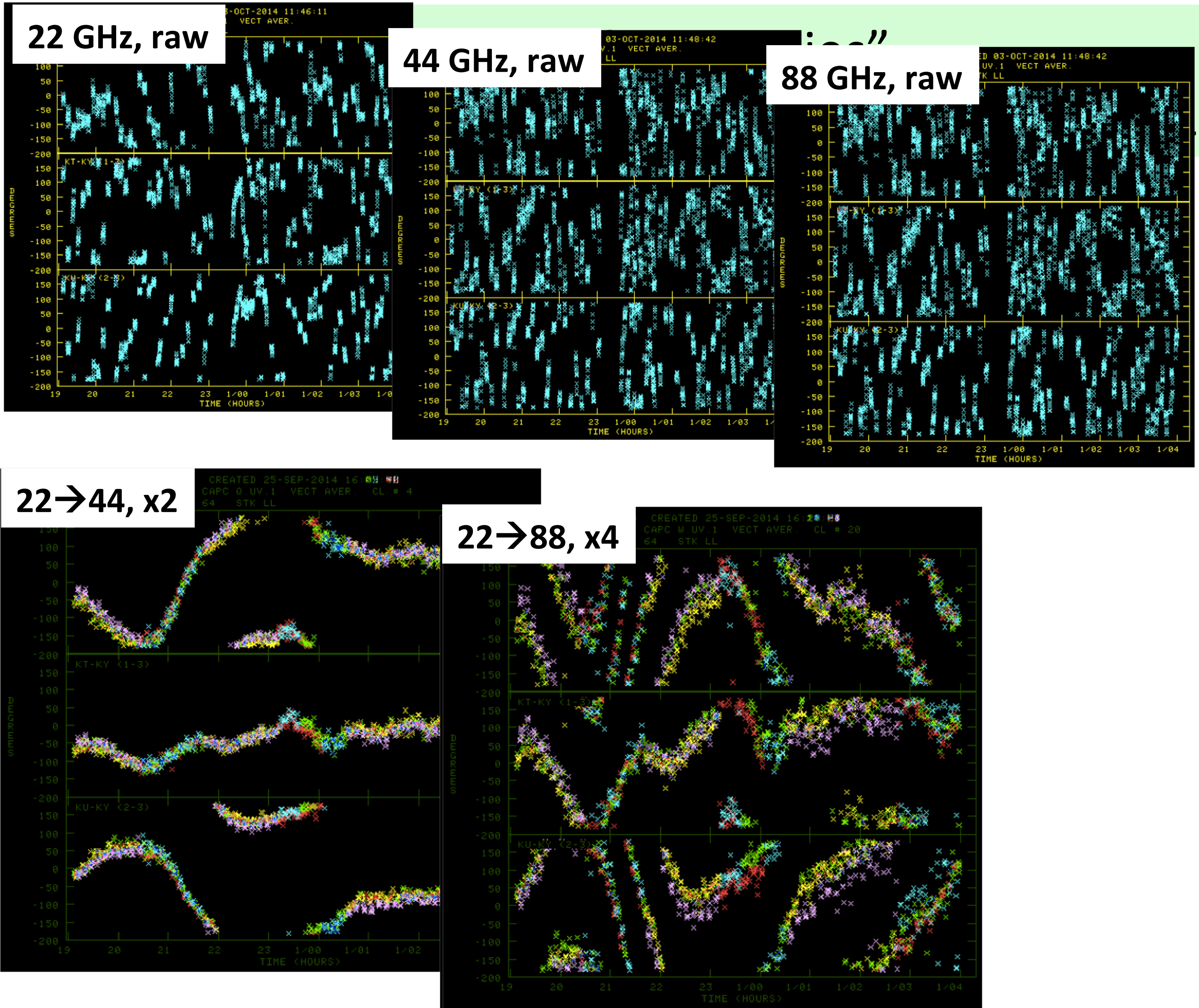
FPT analysis – “2-frequencies”
Residuals increase with R, for a given ν_{low} (22GHz)

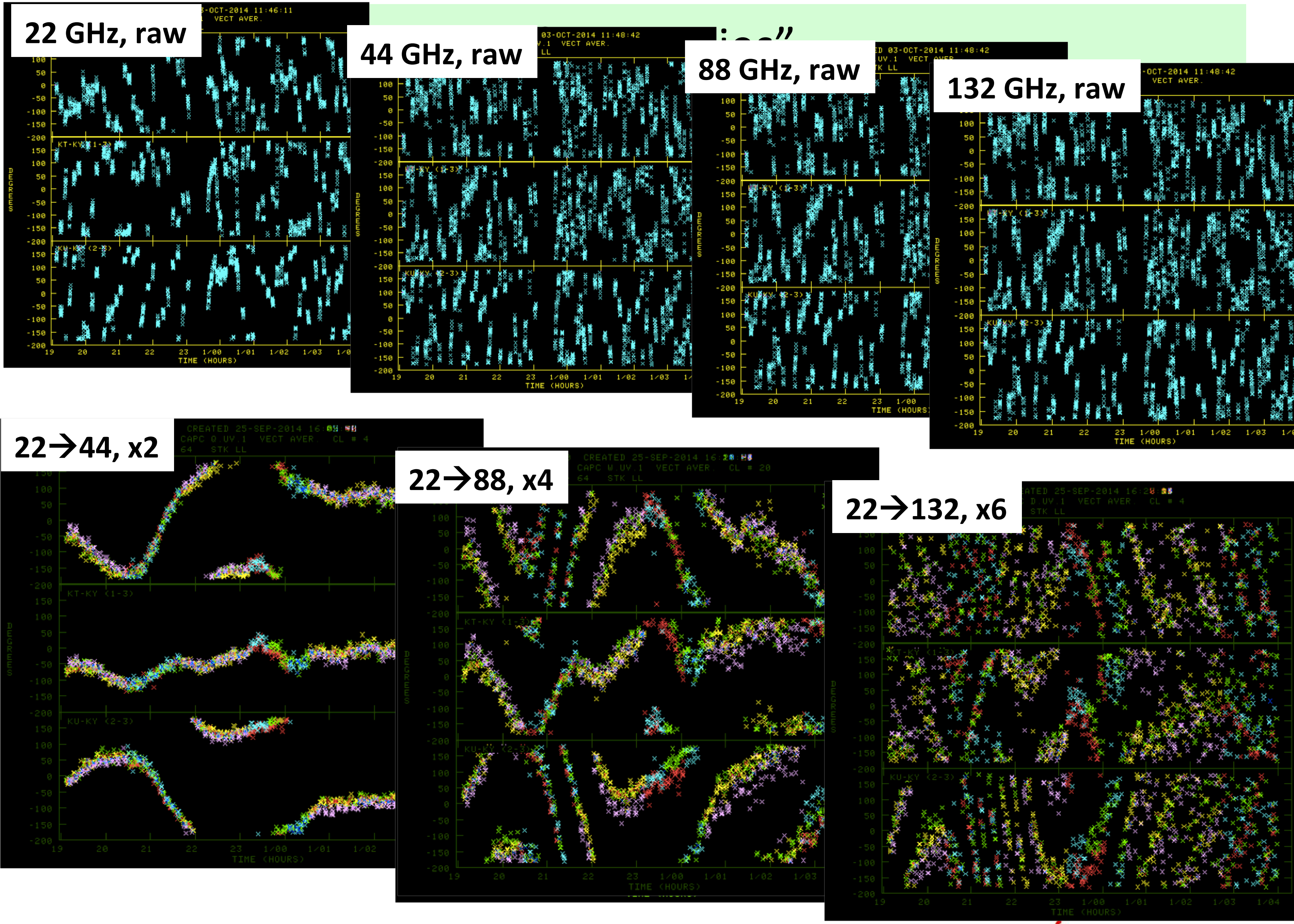
ies”

for a given ν_{low} (22GHz)

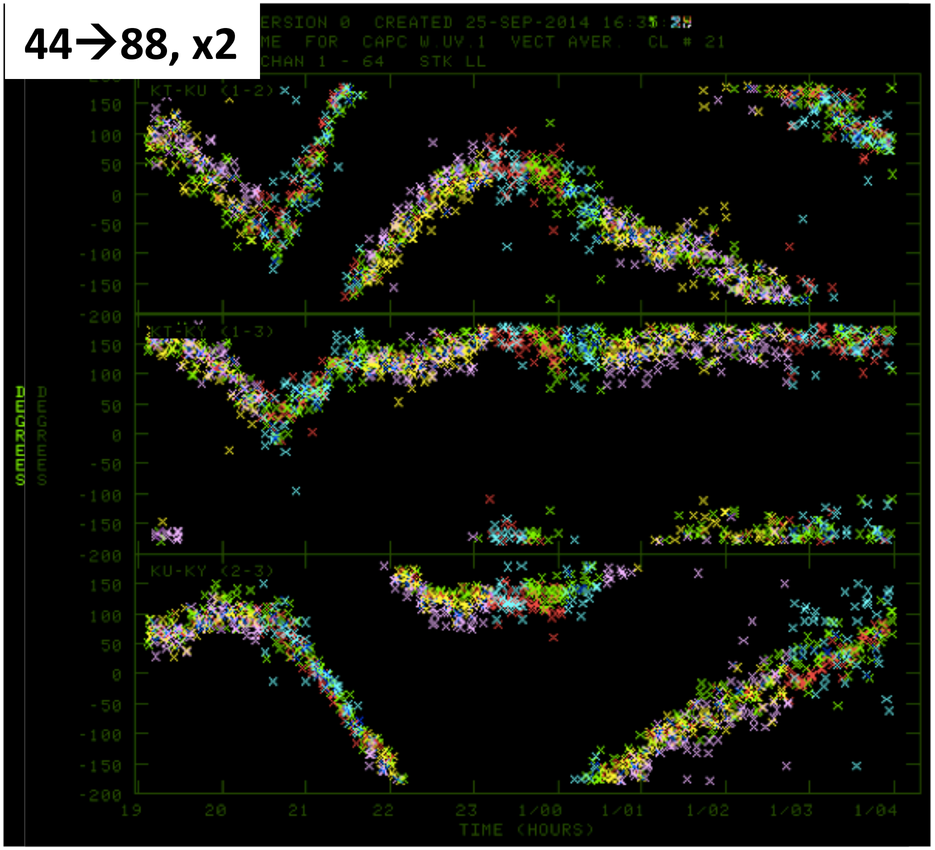


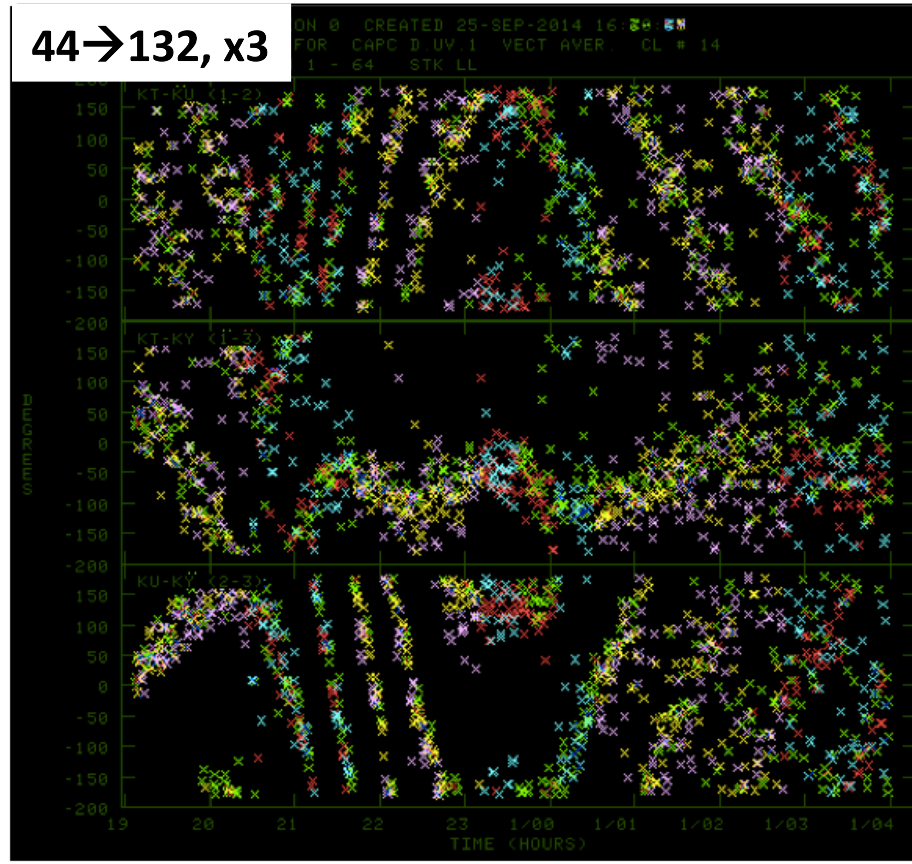



22 GHz, raw
44 GHz, raw
88 GHz, raw
22→44, x2
22→88, x4
DEGREES
TIME (HOURS)
KT-KY (1-3)
KU-KY (2-3)


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

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





SFPR analysis – “2-frequencies” 44 GHz ,132 GHz & “2 sources” 1), 2)

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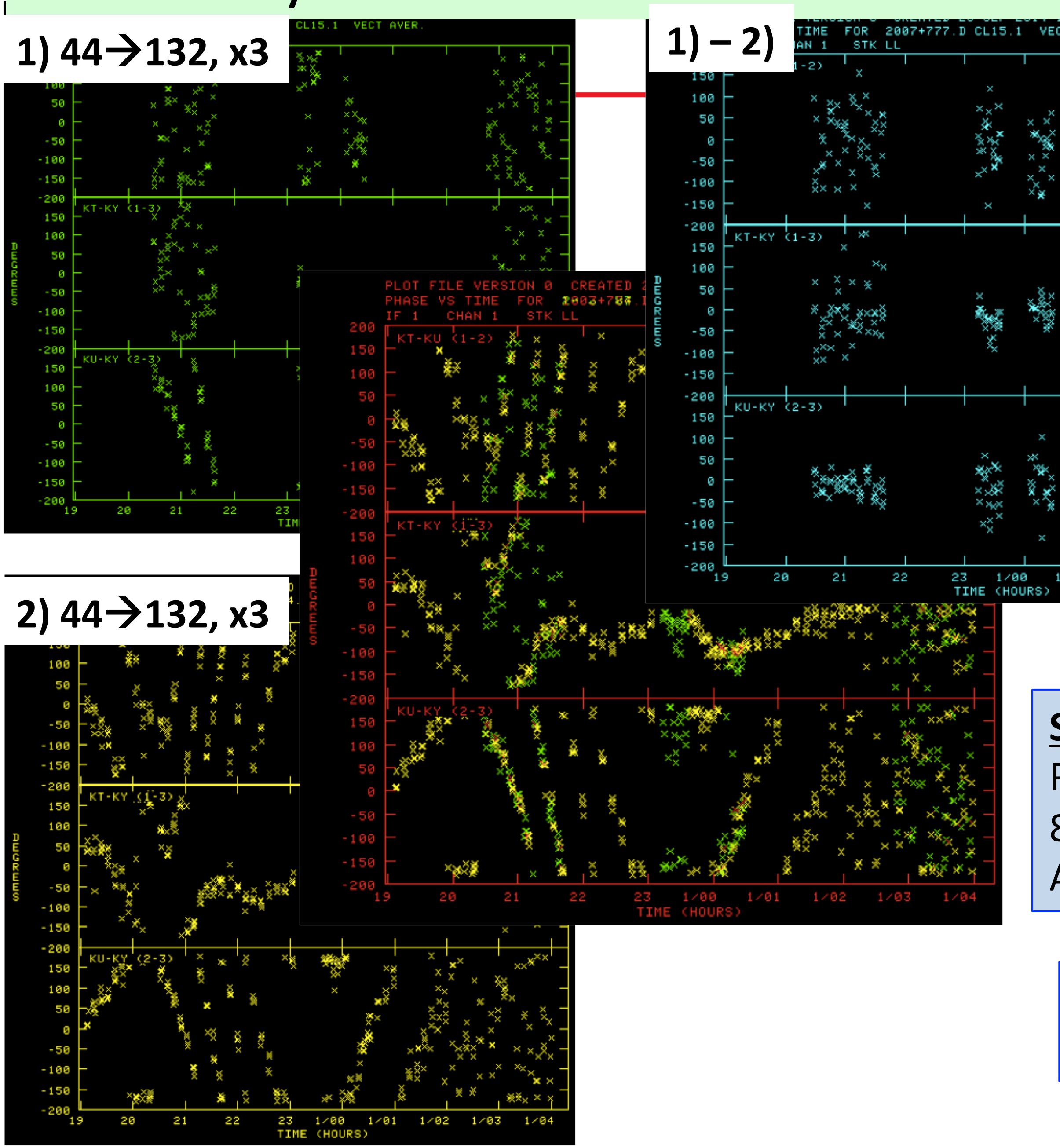
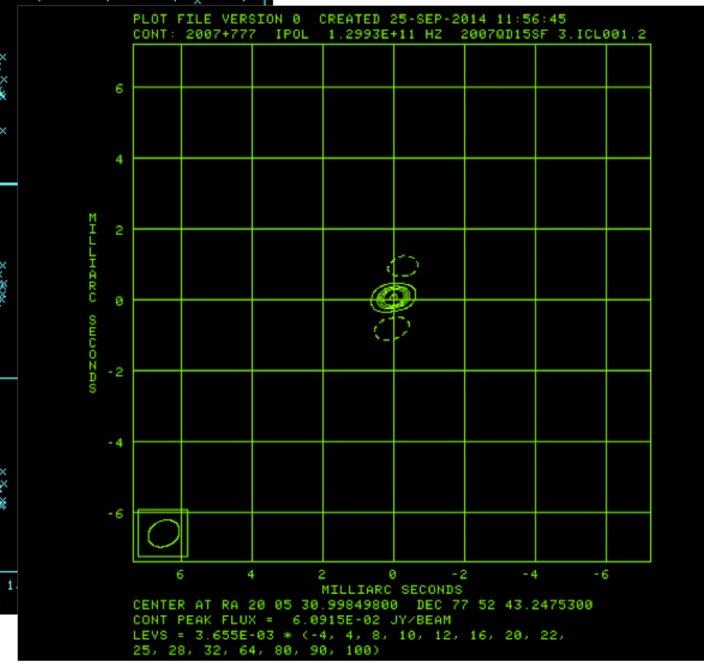
SFPR analysis – 132 GHz with 43GHz: 2007+777 (ref 6.3° away)

1) 44→132, x3

1) – 2)





2) 44→132, x3

SFPR-Map of 2007+777 at 132 GHz:

Peak Flux ~ 61 mJy

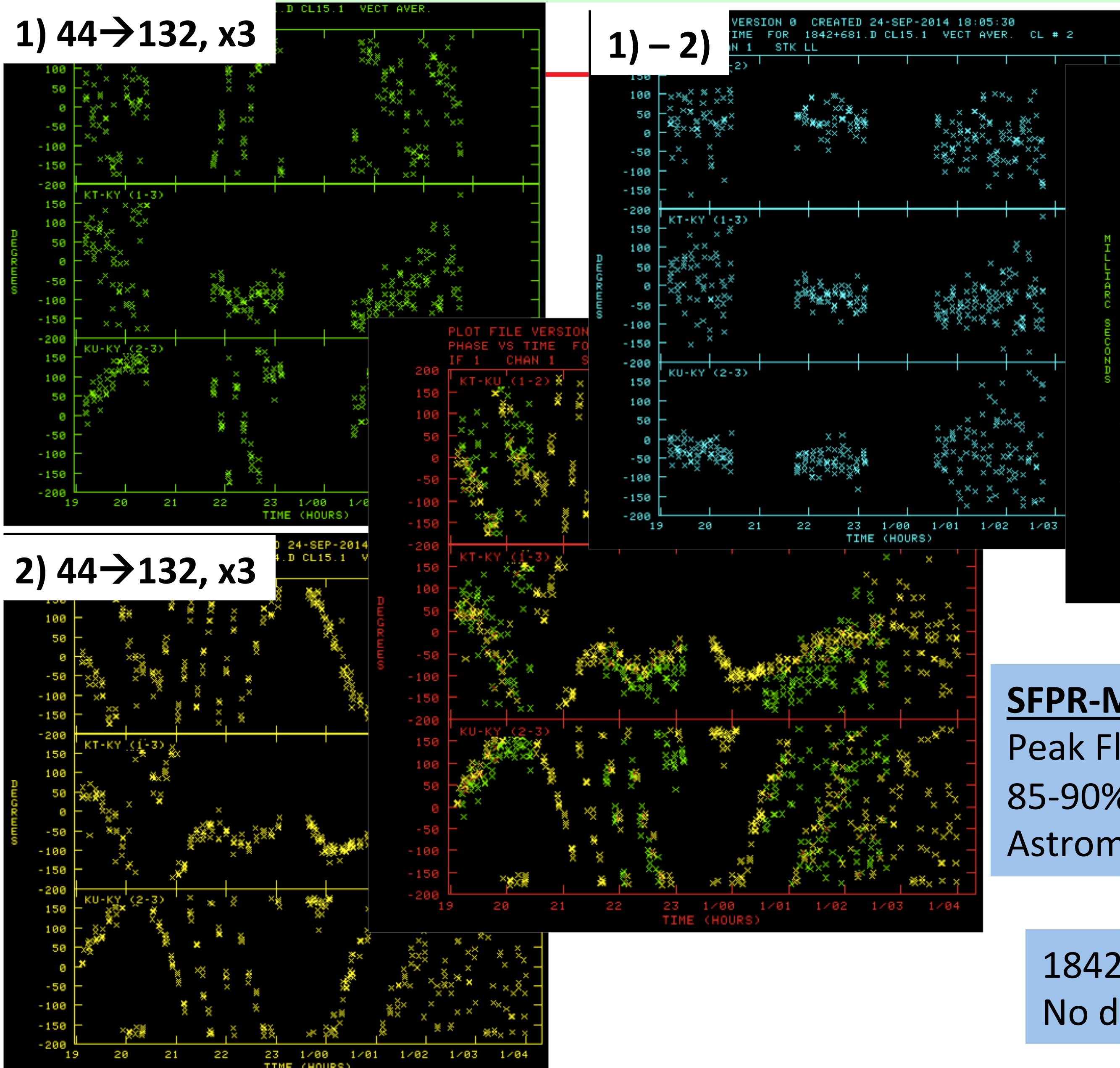
85-90% recovery flux

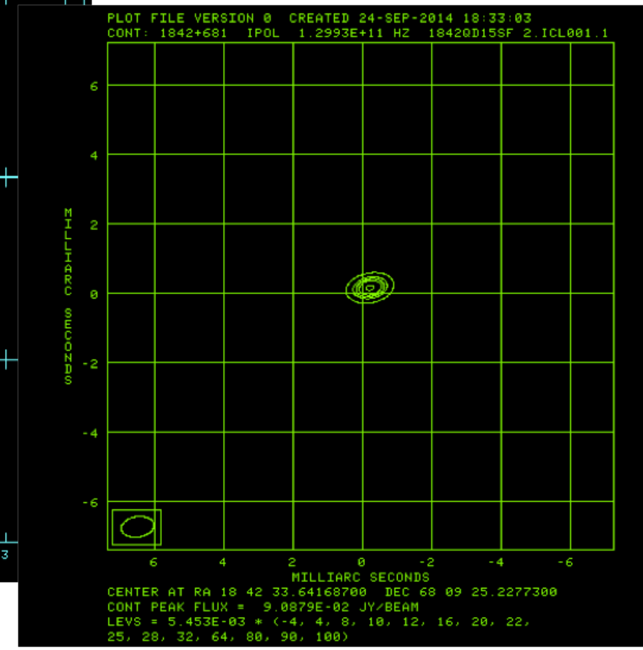
Astrometry ~ (0,50) μas

2007+777 (ref source 6.3° away)

No direct detections at 132 GHz

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





SFPR-Map of 1842+681 at 132 GHz:

Peak Flux ~ 100 mJy

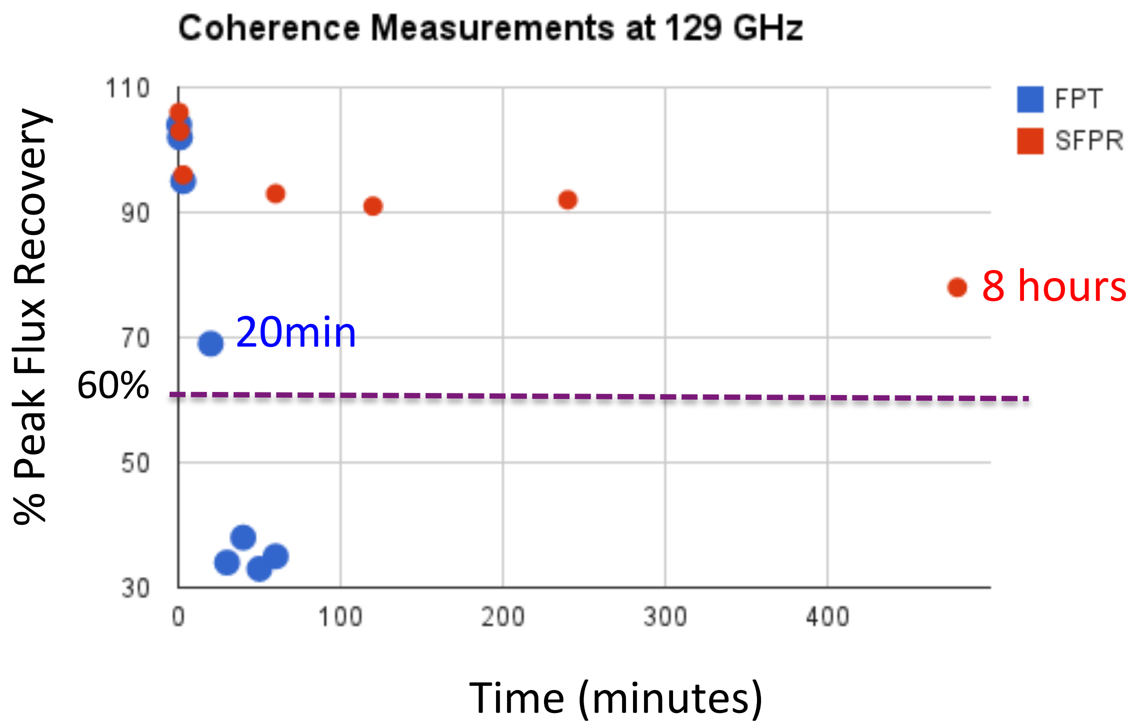
85-90% recovery flux

Astrometry: (-219,144) μas

1842+681 (ref source 11° away)

No direct detections at 132 GHz

Coherence Studies using KVN Observations, for: FPT (single source, 2 freqs) & SFPR (two sources, two freqs) analysis

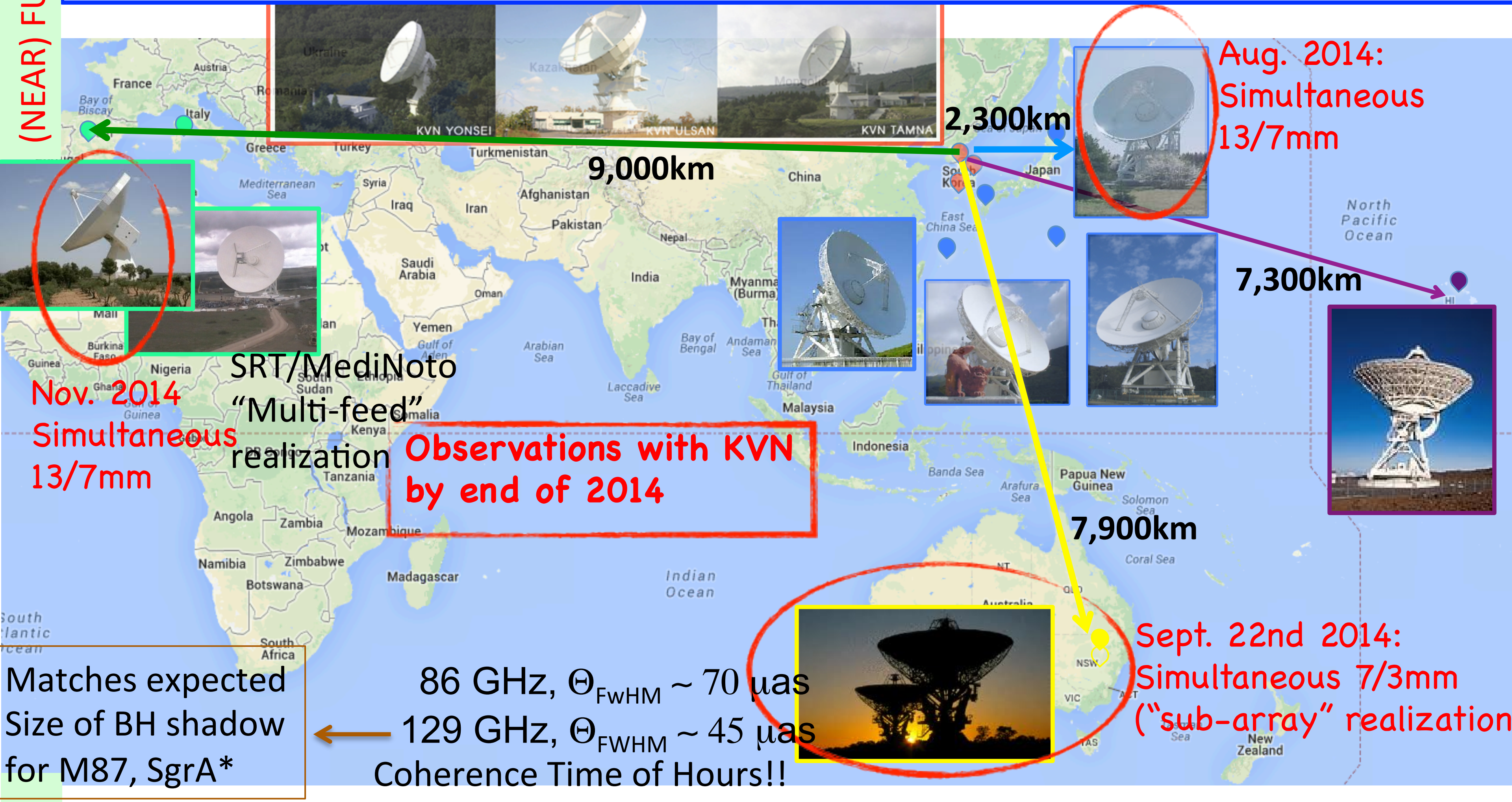


FPT for 44 GHz → 132 GHz increases coherence up to 20 min integration time
SFPR for 44 GHz—> 132 GHz, plus 11^0 ref source, increases coherence up to many hours

(NEAR) FUTURE

The quest for largEST angular resolution (=highEST astrometric accuracy):

A Global "Multi-Frequency" mm-VLBI array



Matches expected Size of BH shadow for M87, SgrA*

86 GHz, $\Theta_{FwHM} \sim 70$ μas

129 GHz, $\Theta_{FWHM} \sim 45$ μas

Coherence Time of Hours!!

FUTURE

Techniques relevant for ALMA (long baselines)

SUMMARY

SFPR: Very robust method for (sub)mm-VLBI

Provides benefits of PR to the highest frequencies

Enables "chromatic" astrometry & Increased coherence time

Simultaneous multi-freq observations vs. ~~fast~~ *slow* frequency switching:

- Much better performance
- More effective use of observing time

Demonstration of SFPR at 132 GHz using KVN

Long baselines planned for near future