Recent Activities with Simultaneous Multi-Frequency Receiving System of the KVN

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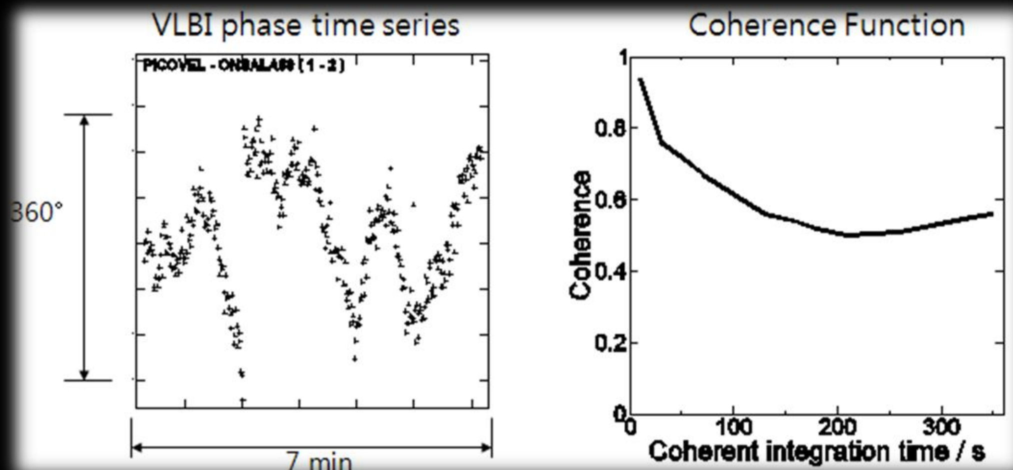
Freq. Phase Transfer

Multi-frequency Receiving System

Errors coming from the ATMOSPHERE are still remain the most serious difficulty which significantly degrade the sensitivity and imaging capability of mm and sub-mm VLBI observation

Coherence



Coherence Function

$$C(T) = \left| \frac{1}{T} \int_0^T e^{i\phi t}\, dt \right|,$$

VLBI Sensitivity

$$S_\nu = (SNR) \frac{8k}{\pi \eta_c} \frac{\sqrt{T_{S_1} T_{S_2}}}{\sqrt{\eta_{A_1} \eta_{A_1}} D_1 D_2 \sqrt{2B\tau_a}}$$

Pico Veleta – Onsala baseline (A. Roy)
Source : BL Lac
Frequency : 86 GHz

Coherence Time

Frequency (GHz)	2	8	15	22	43	86	129
Coherence Time (sec)*	800	200	100	73	37	19	12

*Typical value of atmospheric phase stability ~ 10^{-13}

Frequency Phase Transfer (FPT)

$$\Phi^h = \Phi^h{}_{str} + 2\pi\nu^h(\tau_g + \tau_C + \tau_{inst} + \tau_{trop} + \tau_{ion}) + \Phi^h{}_{LO}$$

$$\Phi^l = \Phi^l{}_{str} + 2\pi\nu^l(\tau_g + \tau_C + \tau_{inst} + \tau_{trop} + \tau_{ion}) + \Phi^l{}_{LO}$$

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Self-calibration at lower frequency

$$\Phi^l{}_{str}$$

$$2\pi\nu^l(\tau_g + \tau_C + \tau_{inst} + \tau_{trop} + \tau_{ion}) + \Phi^l{}_{LO}$$

$$\Delta\Phi = \Phi^h - r\Phi^l$$

$$r = \nu_h / \nu_l$$

$$\Delta\Phi = \Phi_h - \frac{\nu_h}{\nu_l}\Phi_l = \Phi_h{}^{str} + 2\pi\nu_h(\tau_h{}^g - \tau^g{}_l) - 2\pi\left(1 - \frac{\nu_h^2}{\nu_l^2}\right)\frac{\nu_0^2}{\nu_h^2}\tau^{ion} + (\Phi_h{}^{LO} - \frac{\nu_h}{\nu_l}\Phi_l{}^{LO})$$

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$$r = \nu_h / \nu_l$$

slow varying term

$$\Delta\Phi = \Phi_h - \frac{\nu_h}{\nu_l}\Phi_l = \Phi_h{}^{str} + 2\pi\nu_h(\tau_h{}^g - \tau^g{}_l) - 2\pi\left(1 - \frac{\nu_h^2}{\nu_l^2}\right)\frac{\nu_0^2}{\nu_h^2}\tau^{ion} + (\Phi_h{}^{LO} - \frac{\nu_h}{\nu_l}\Phi_l{}^{LO})$$

Source Structure

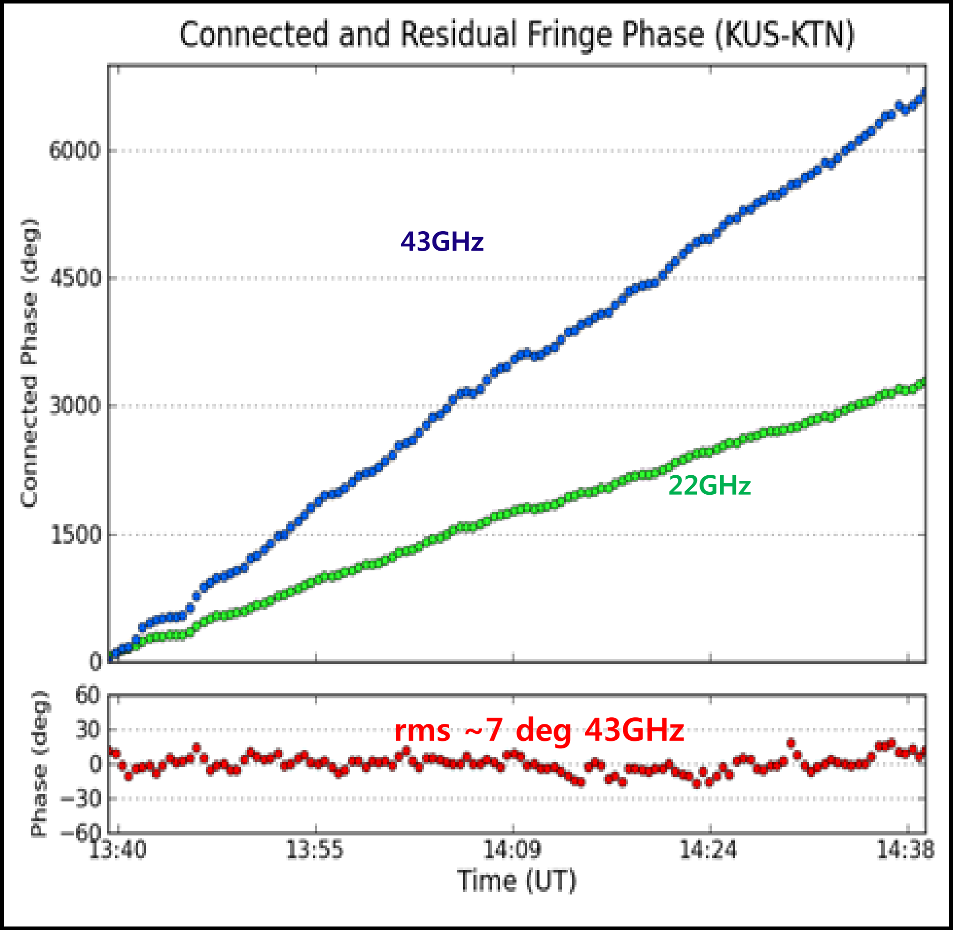
Core-shift diff in maser lines

ionosphere

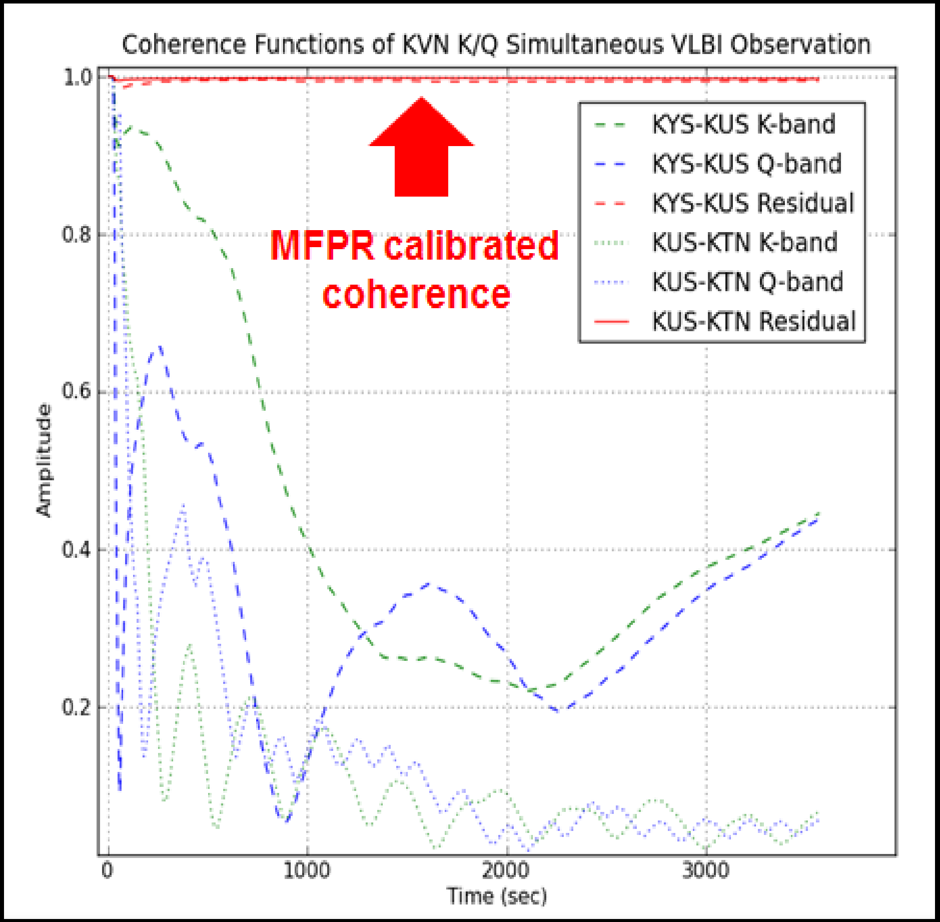
instrument

By doing Self-calibration again for longer solution interval, we can get an image at higher frequency

First KVN Multi-Frequency Phase Referencing Observation



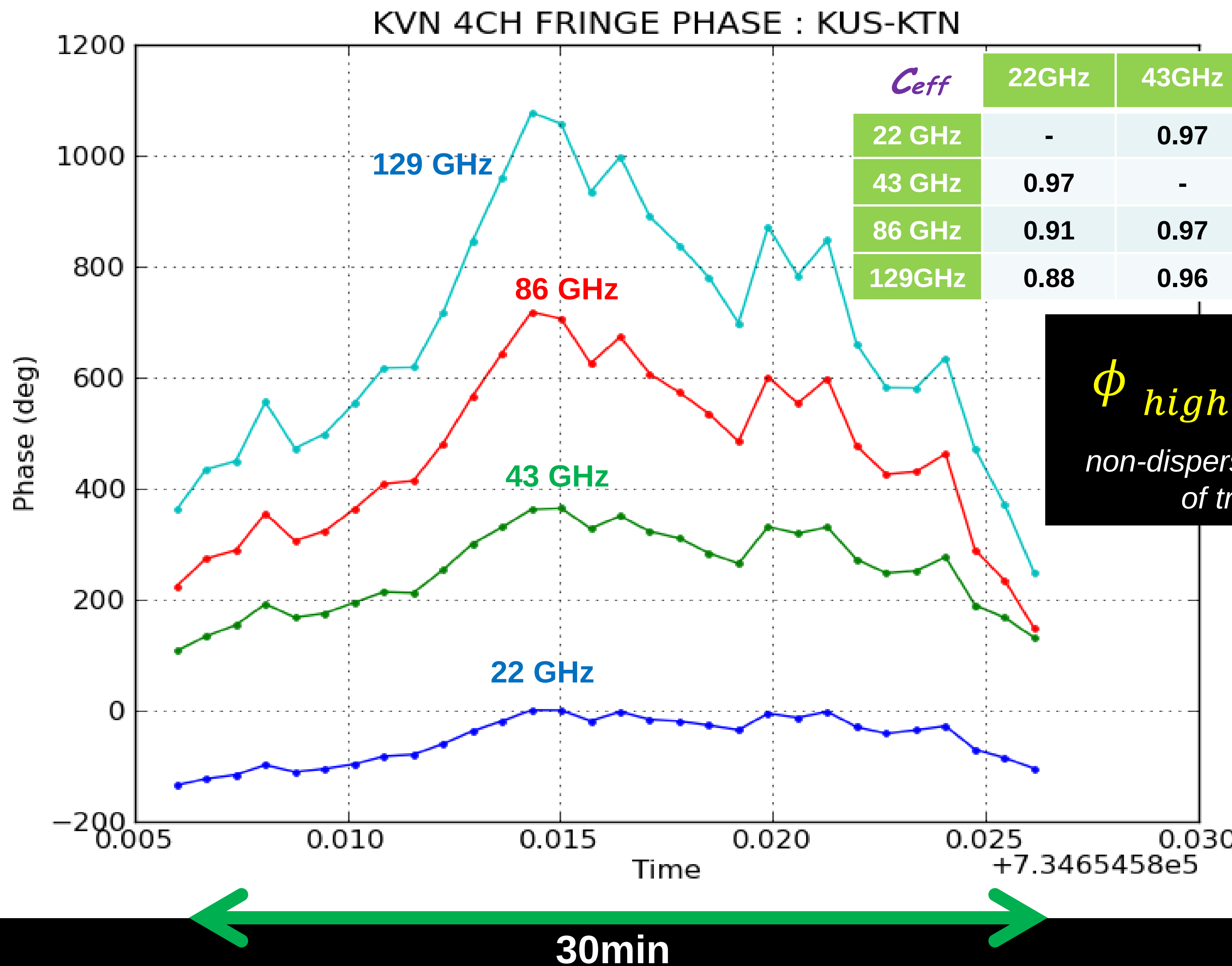
22/43GHz Phase Solutions



Coherence

- Estimated astrometric accuracy ~ 60 μas

KVN Multi-Freq. Simultaneous Observation



C_{eff}	22GHz	43GHz	86GHz	129GHz
22 GHz	-	0.97	0.91	0.88
43 GHz	0.97	-	0.97	0.96
86 GHz	0.91	0.97	-	0.99
129GHz	0.88	0.96	0.99	-

$$\phi_{high} \propto \frac{\nu_h}{\nu_l} \phi_{low}$$

non-dispersive characteristic of troposphere

An Ideal System in Mm-VLBI

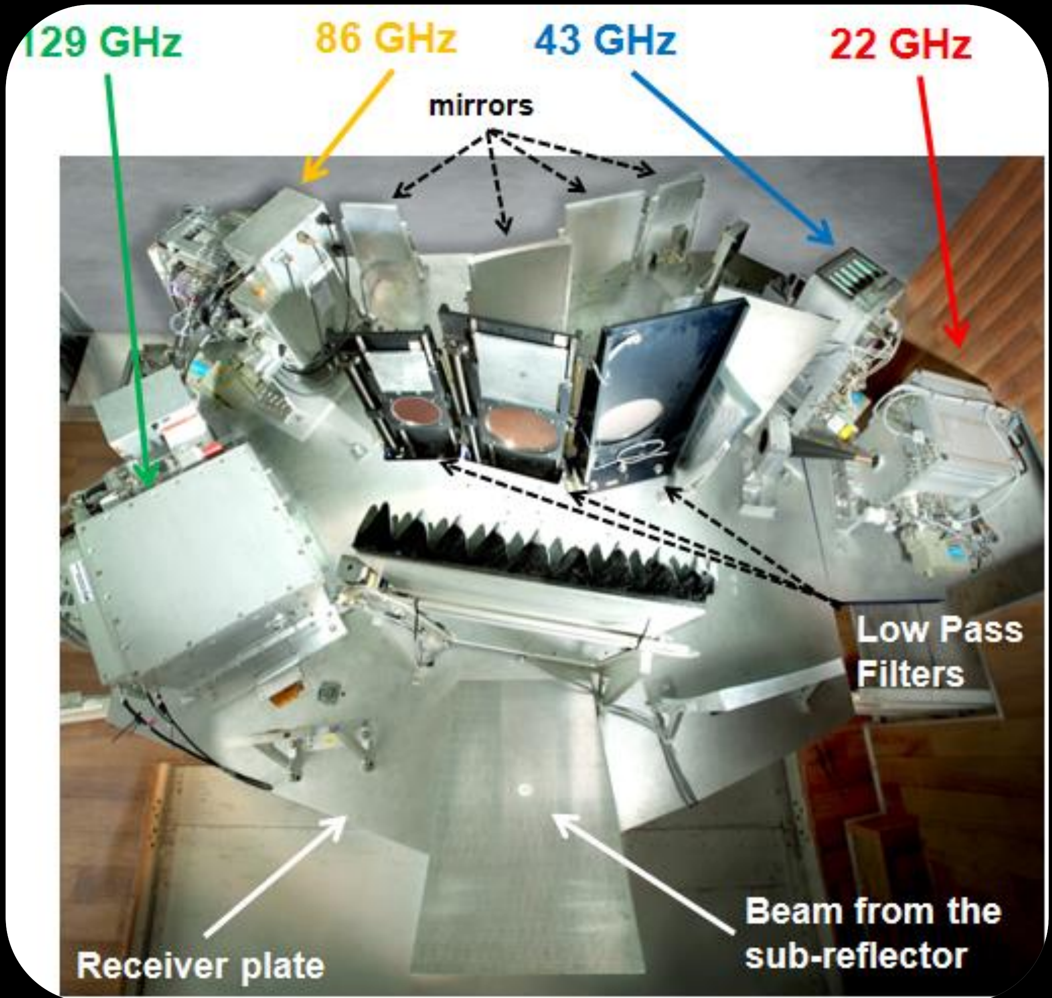
KVN
Multi-Frequency Feeds

Target itself is the reference
→ resolving the reference source problem

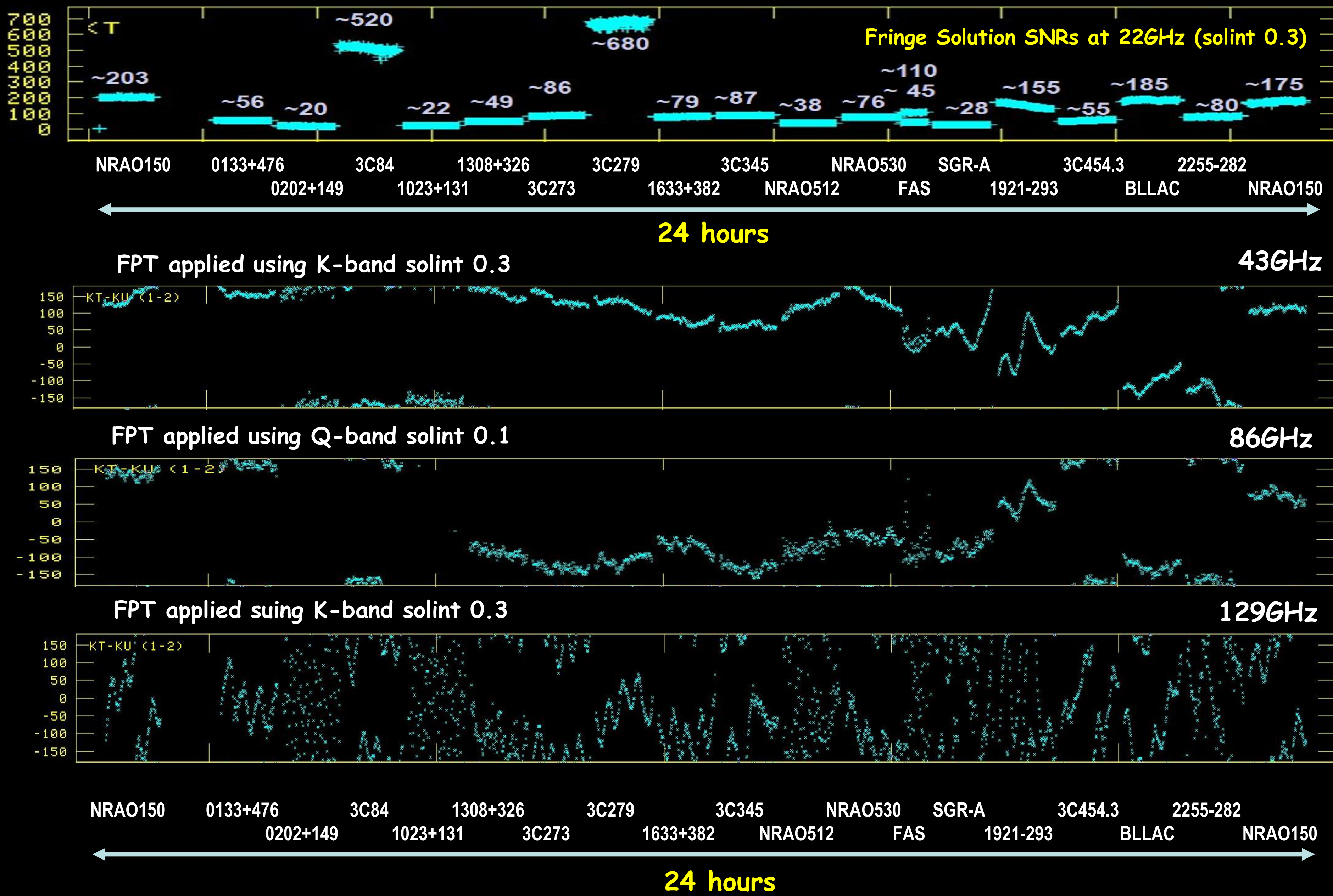
No coherence loss
→ due to the same sky position

Integrate mm VLBI fringes as long as a single dish telescope does
→ weak source detection at mm

New possibilities of science such as AGN core shift & H_2O/SiO masers by overlapping the VLBI images of radio sources at different frequencies



High frequency VLBI Phase Calibration by Lower Frequency Phase Solutions



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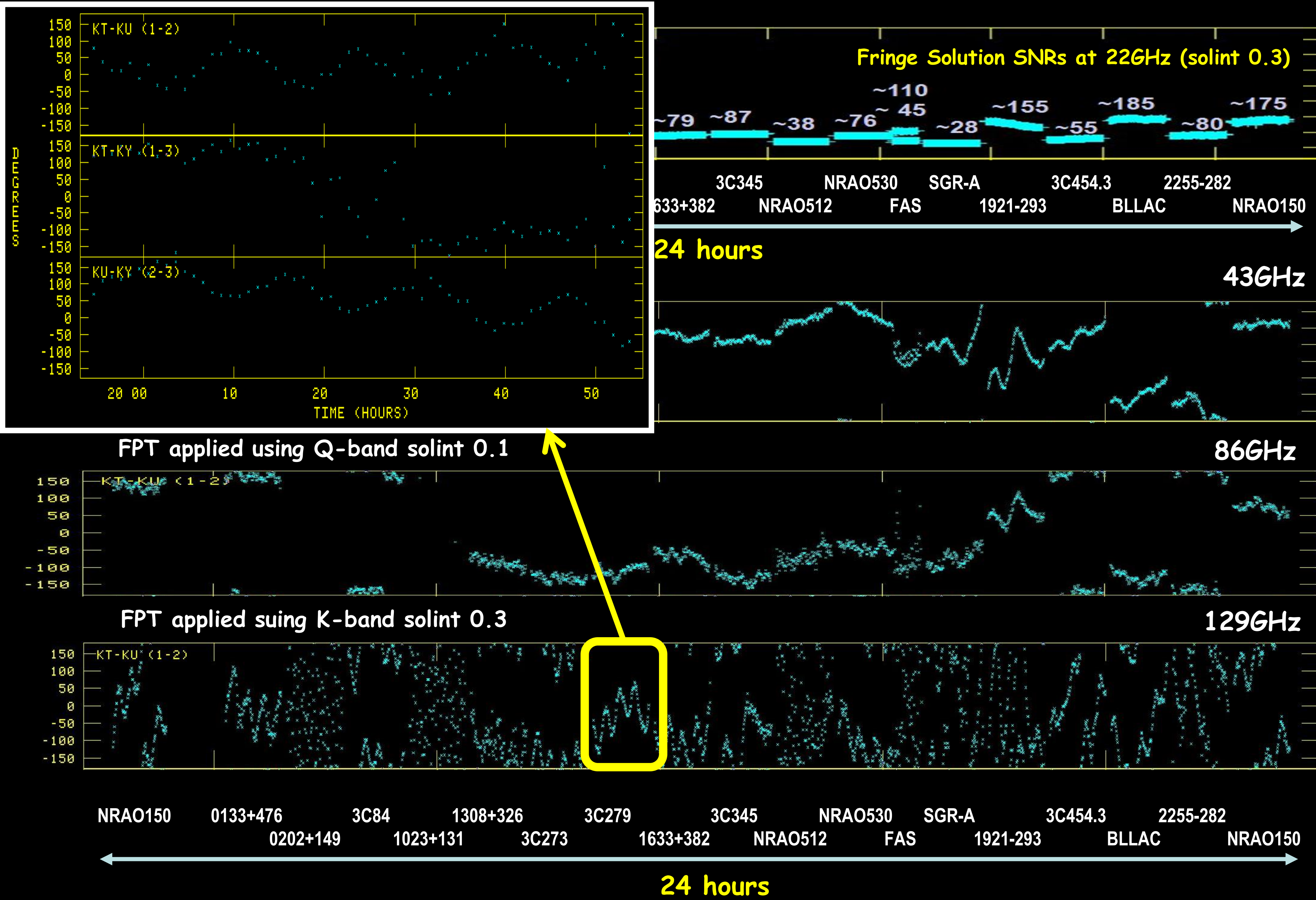

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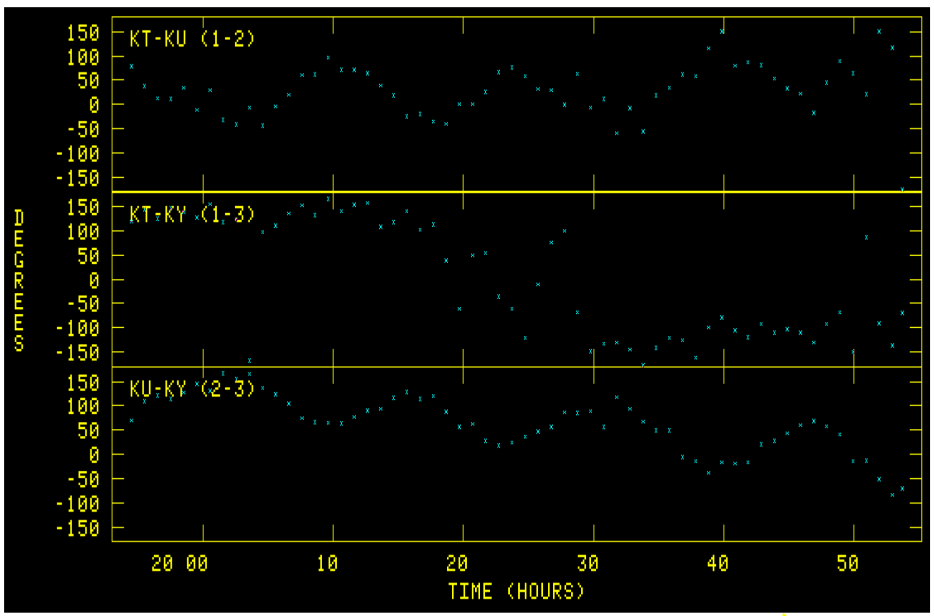
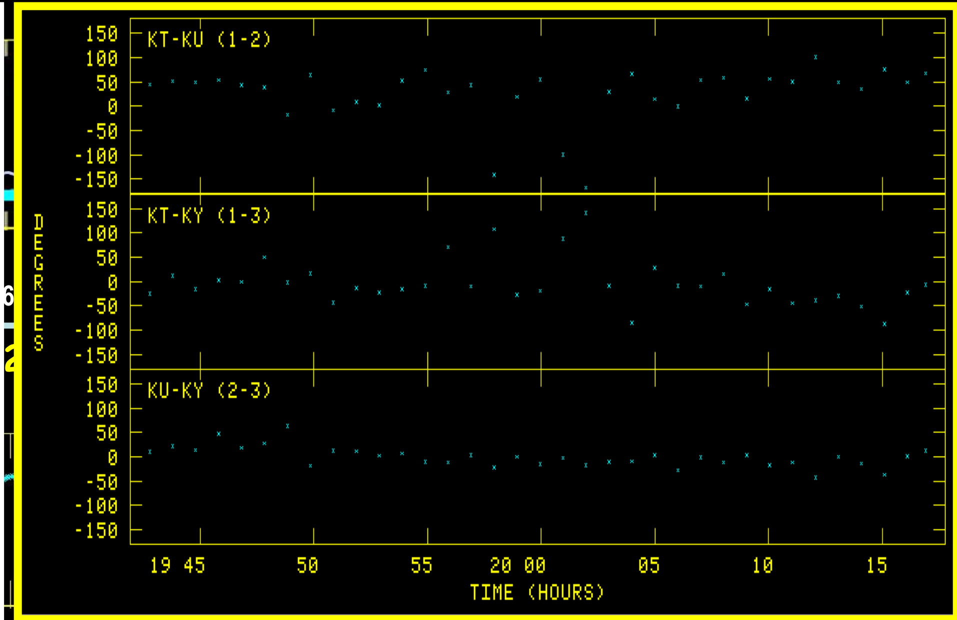
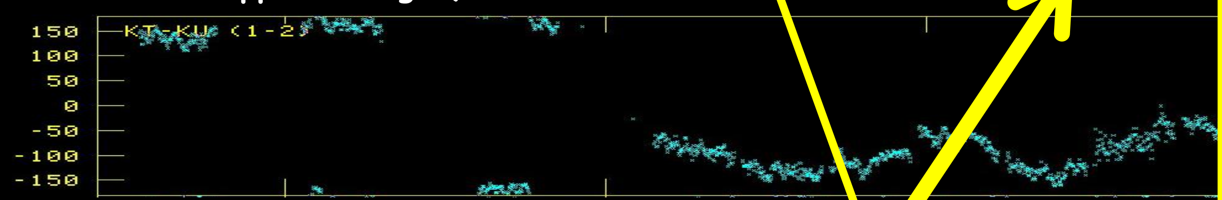
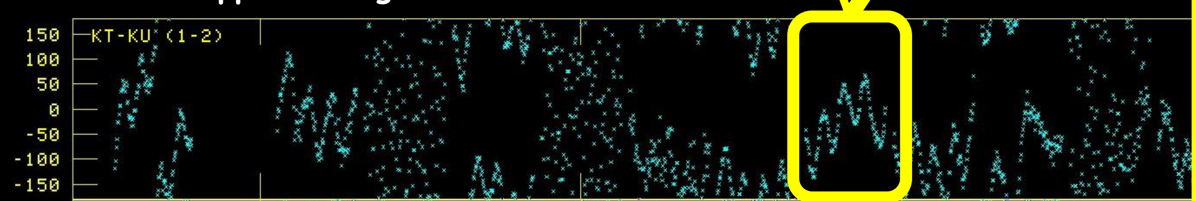




FPT applied using Q-band solint 0.1



FPT applied suing K-band solint 0.3

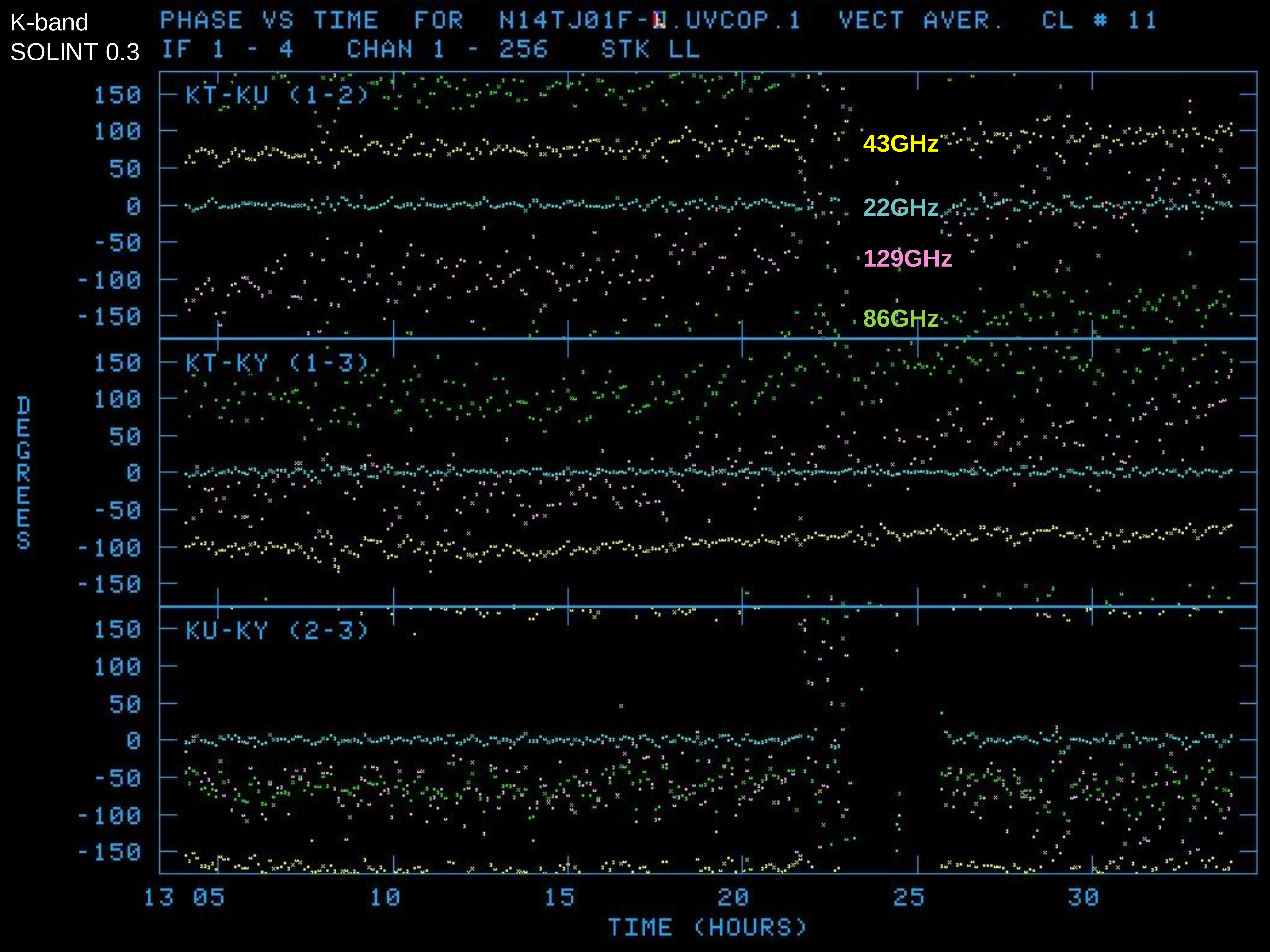


New thermal control system at KVN Yonsei Rx Room

NRAO150 0133+476 3C84 1308+326 3C279 3C345 NRAO

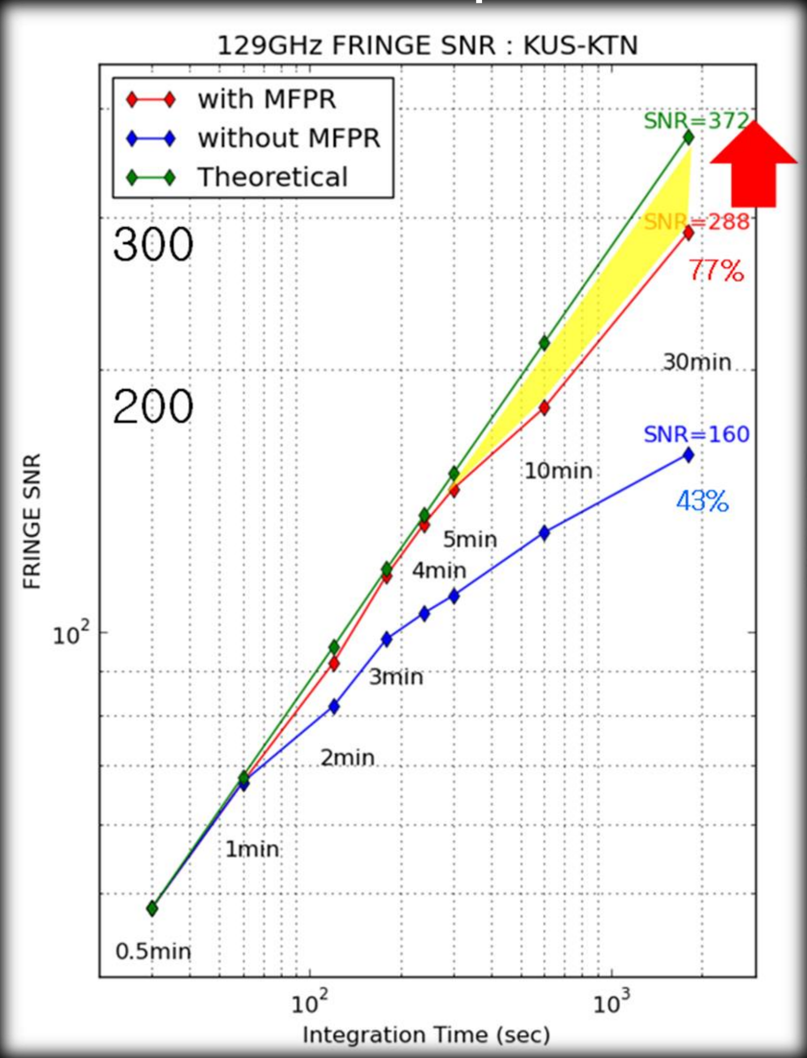
0202+149 1023+131 3C273 1633+382 NRAO512

24 hours


K-band
SOLINT 0.3
PHASE VS TIME FOR N14TJ01F-.UVCOP.1 VECT AVER. CL # 11
IF 1 - 4 CHAN 1 - 256 STK LL
KT-KU (1-2)
KT-KY (1-3)
KU-KY (2-3)
43GHz
22GHz
129GHz
86GHz
DEGREES
150
100
50
0
-50
-100
-150
13 05
10
15
20
25
30
TIME (HOURS)

Increase coherence time → weak source detection with high SNR

Before Rx Room Temp. Stabilization



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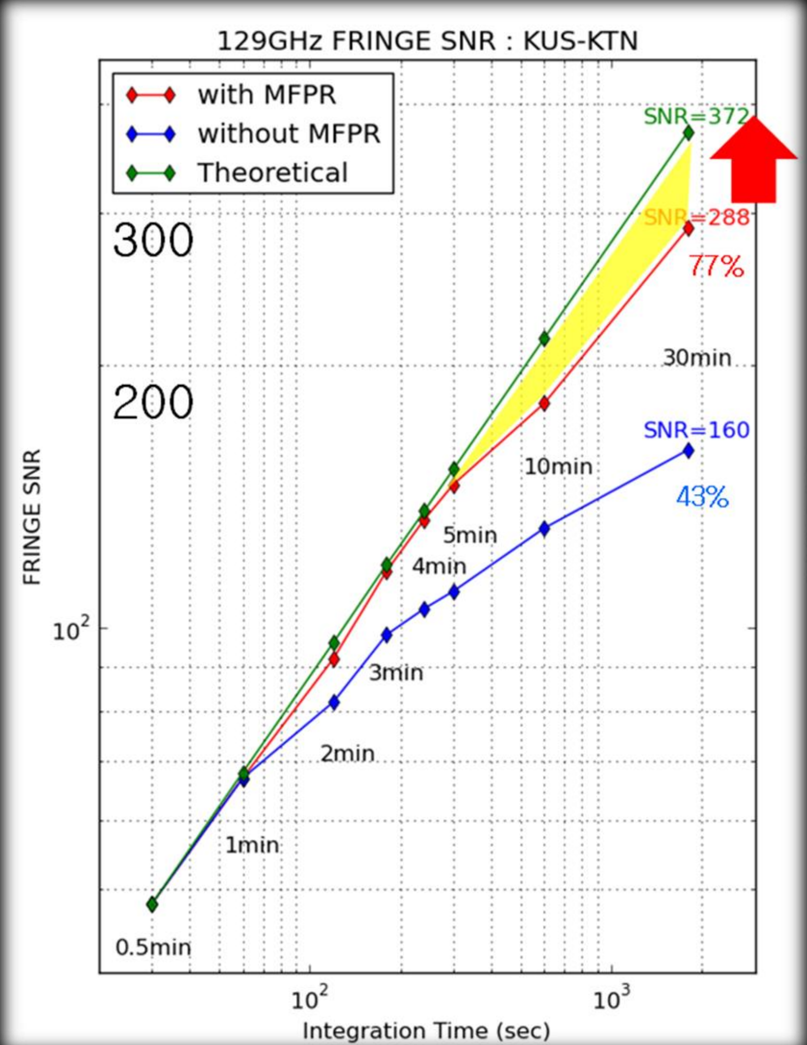
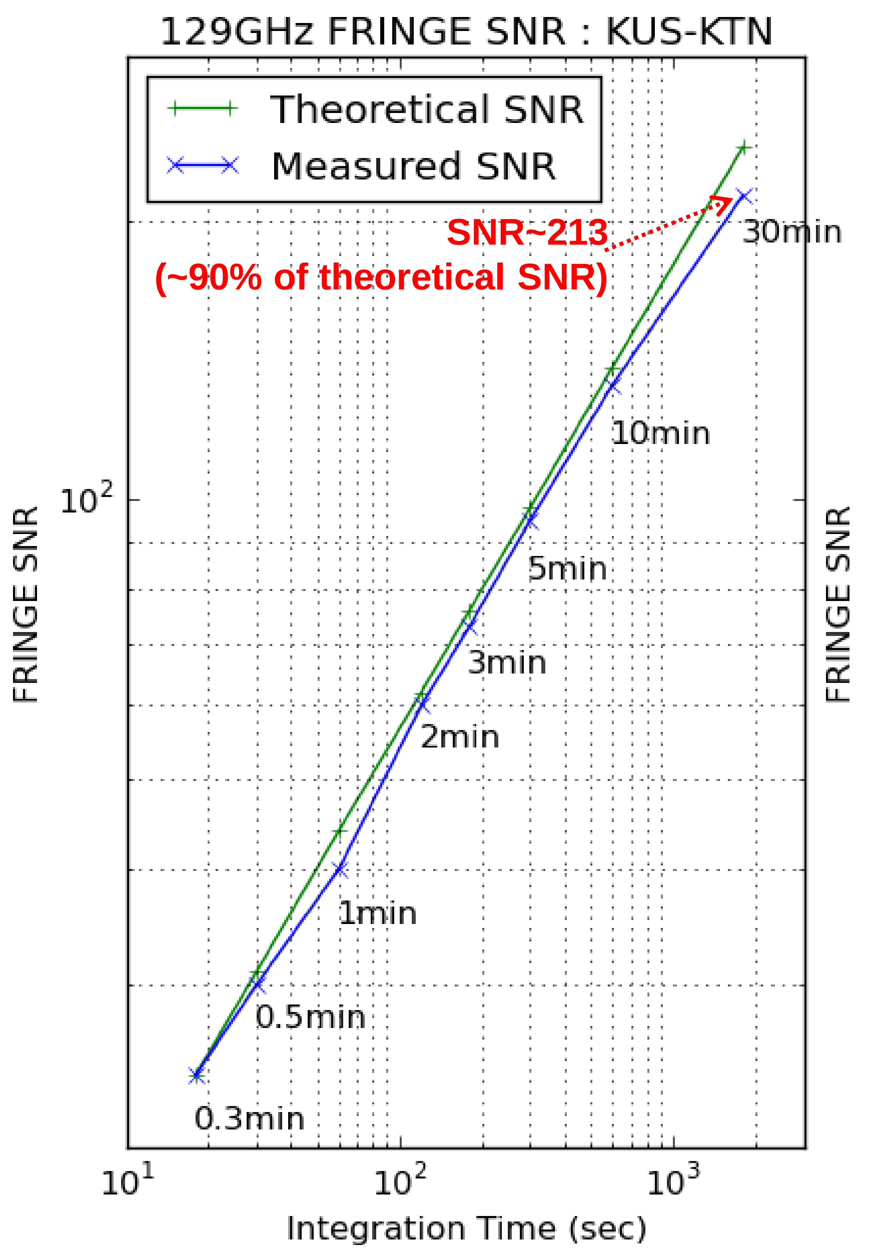


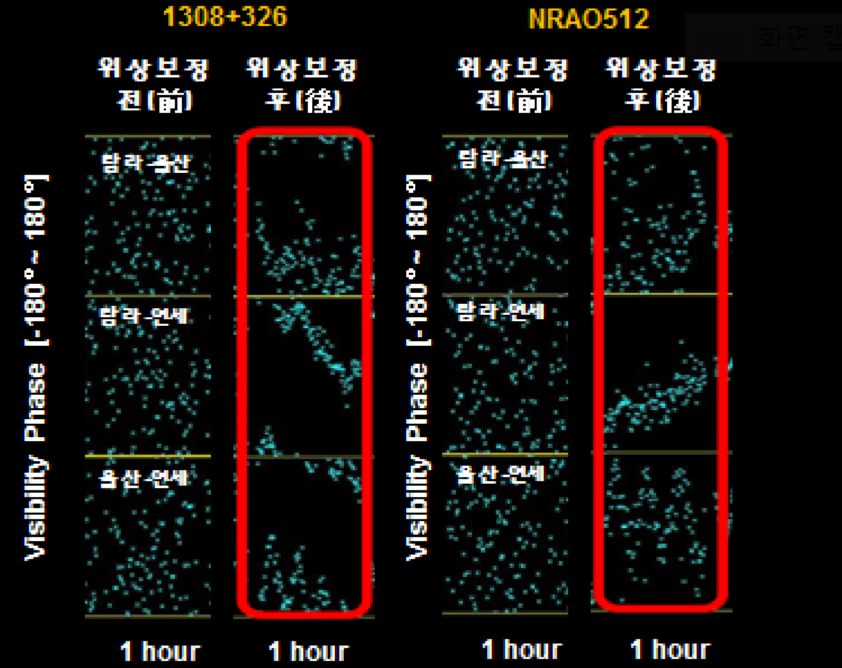
After New Rx Room Temp. Stabilization ➔



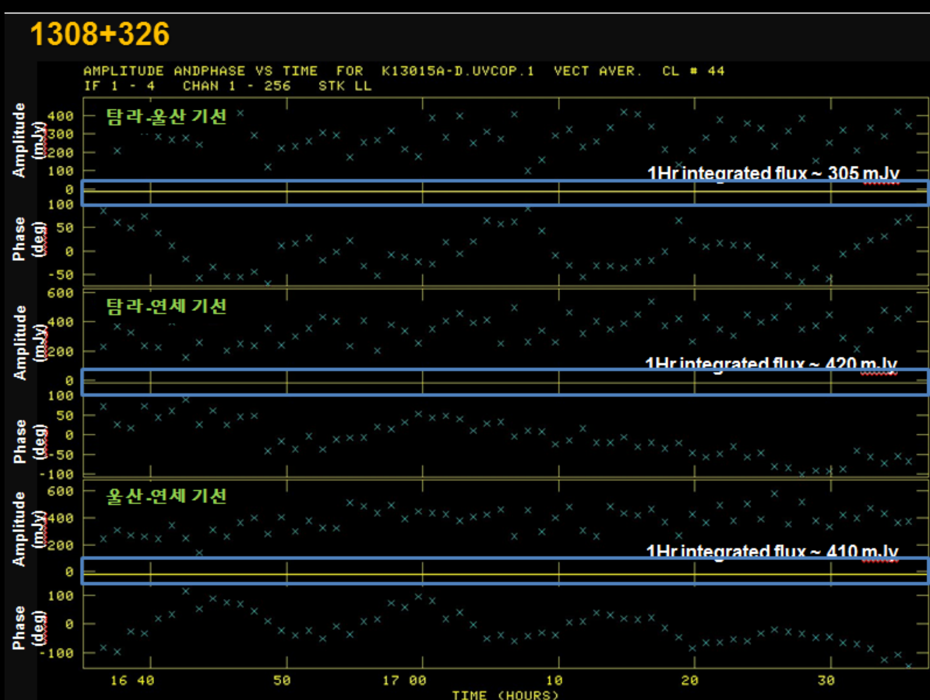
Source Detection at High Frequency

- 1308+326 & NRAO512 were not detected at D-band
- After applying MFPR with1 hour integration, these sources are detected with high SNRs (~130, ~80)
  ➔ The FIRST detection of 1308+326 & NRAO512 at 129GHz

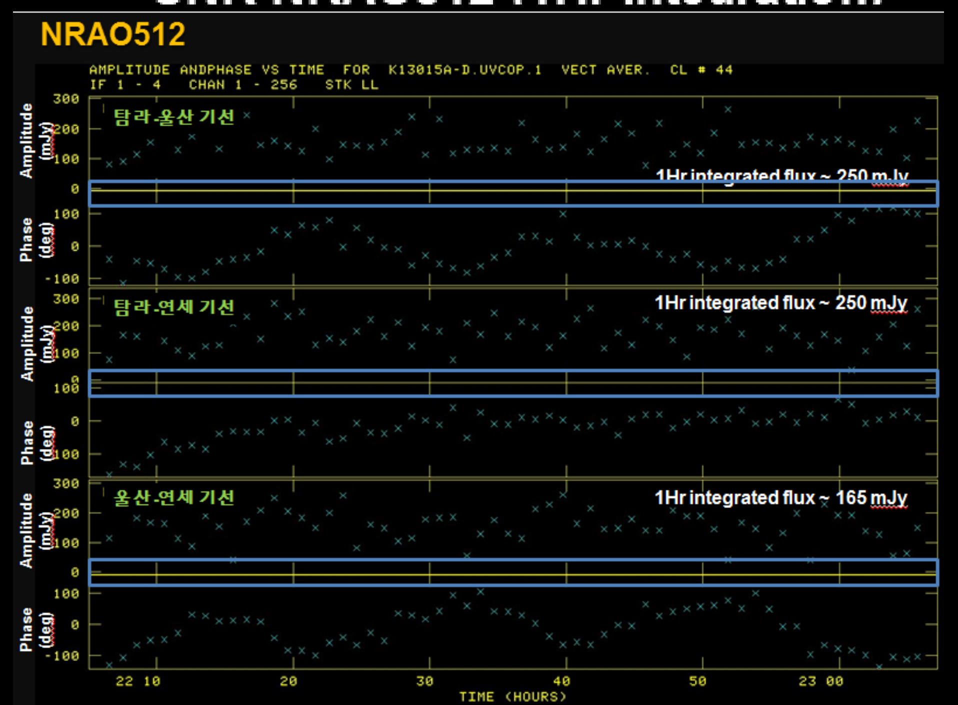
- SNR : 1308+326 ~ 130, NRAO512 ~ 100
- Flux : 1308+326 : 300~420 mJy
  NRAO512 : 160~250 mJy



SNR 1308+326 (1Hr integration)



SNR NRAO512 (1Hr integration)



Sensitivity

KVN 1 Gbps 4CH operation: 64MHz BW for 22/43/86/129GHz each

Frequency Band	22 GHz	43 GHz	86 GHz	129 GHz
Bandwidth (MHz)	64			
System temperature (K)	80	90	180	200
SEFD (Jy)	981	1196	2870	3986
Integration time (sec)	30 sec	1800 (30 min)		
Sensitivity (mJy)	18	2.8	6.8	9.4
5σ Sensitivity (mJy)	90.0	14.1	34.0	47.2

KVN 8 Gbps 4CH operation: 512MHz BW for 22/43/86/129GHz each

Frequency Band	22 GHz	43 GHz	86 GHz	129 GHz
Bandwidth (MHz)	512			
System temperature (K)	80	90	180	200
SEFD (Jy)	981	1196	2870	3986
Integration time (sec)	30 sec	1800 (30 min)		
Sensitivity (mJy)	6.4	1.0	2.4	3.4
5σ Sensitivity (mJy)	32.1	5.0	12.1	16.9

※ 8Gbps Operation : FILA10G + Mark6

Sensitivity

KVN 1 Gbps 4CH operation: 64MHz BW for 22/43/86/129GHz each

Frequency Band	22 GHz	43 GHz	86 GHz	129 GHz
Bandwidth (MHz)	64			
System temperature (K)	80	90	180	200
SEFD (Jy)	981	1196	2870	[illegible]
Integration time (sec)	30 sec	[illegible]		
Sensitivity (mJy)	18	[illegible]	[illegible]	[illegible]
5σ Sensitivity (mJy)	[illegible]	[illegible]	[illegible]	[illegible]

> Finding many weak sources at high frequencies (KVN mm-VLBI source catalogue) will open a new era of mm-VLBI and provide an important basis of high-freq. catalogue for ALMA.

KVN [illegible] 22/43/86/129GHz each

[illegible]	[illegible]	43 GHz	86 GHz	129 GHz
[illegible]	512			
[illegible] temperature (K)	80	90	180	200
SEFD (Jy)	981	1196	2870	3986
Integration time (sec)	30 sec	1800 (30 min)		
Sensitivity (mJy)	6.4	1.0	2.4	3.4
5σ Sensitivity (mJy)	32.1	5.0	12.1	16.9

※ 8Gbps Operation : FILA10G + Mark6

Multi-Frequency AGN Survey

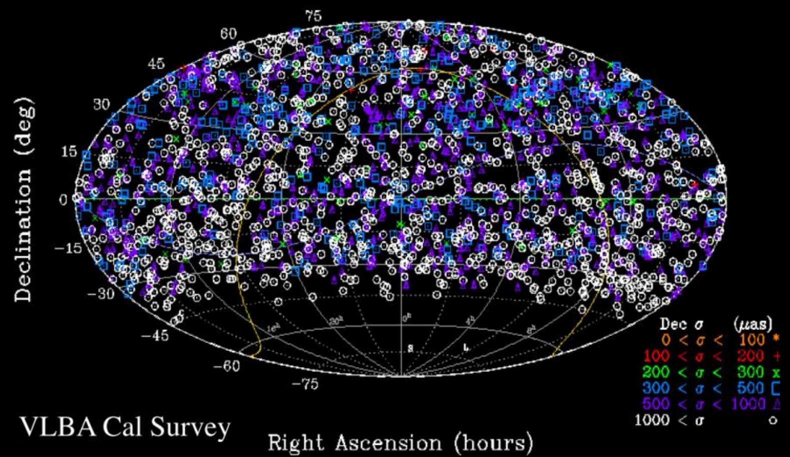
New mm-VLBI source catalogue

VLBI Surveys

Name	Wavelength	# of Sources	Reference
CJF survey	18 & 6 cm	293	Pollack et al. 2003
ICRF/RDV	13 & 3.6 cm	~ 500	Ojha et al. 2004
VLBA Calibrator Survey	13 & 3.6 cm	> 3400	Kovalev et al. 2007
VSOP VLBApls	6 cm	374	Fomalont et al. 2000
VSOP Survey	6 cm	~ 300	Dodson et al. 2008
VIPS	6 cm	1127	Helmboldt et al. 2007
2cm Survey	2 cm	250	Kovalev et al. 2005
MOJAVE	2 cm	> 133	Lister & Homan 2005
VERA FSS / GaPS	1.35 cm	500	Petrov et al. 2007
ICRF 22 & 43 GHz	1.37 & 0.7 cm	~100	Lanyi et al. 2010
GMVA 3mm	3 mm	123	Lee et al. 2008
TANAMI	3.5 & 1.3 cm	80	Ojha et al. 2010

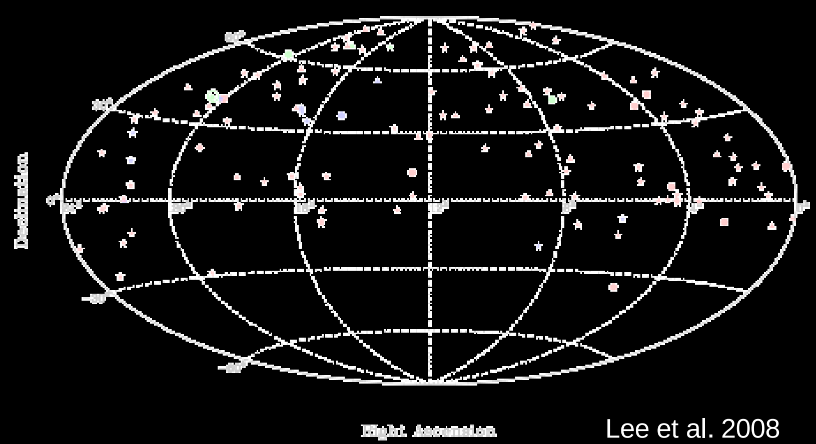
Up to now...

- Number of VLBI sources at mm-wavelengths are still very limited
  - more than ~3400 sources are available at 3.6 cm, while ~110 sources are available shorter than 3 mm



Beasely et al. 2002

3414 sources at 3.6 cm

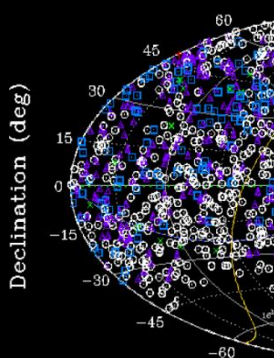


Lee et al. 2008

109 sources at 3 mm

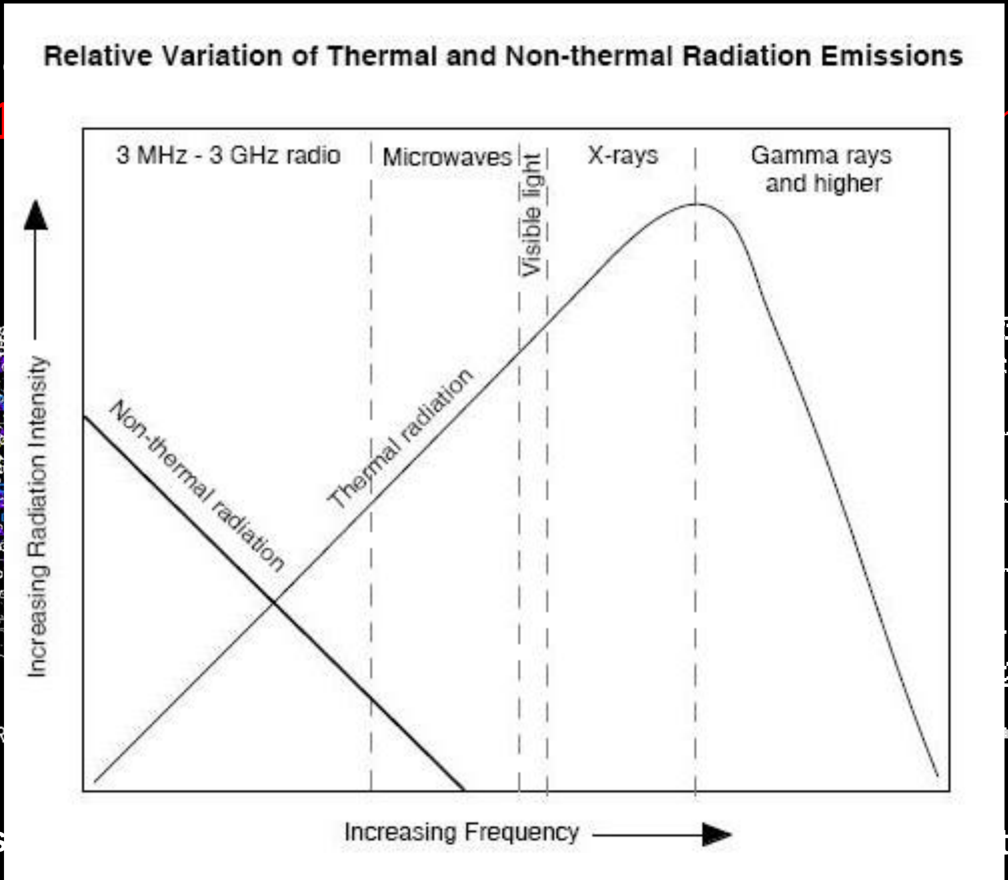
Up to now...

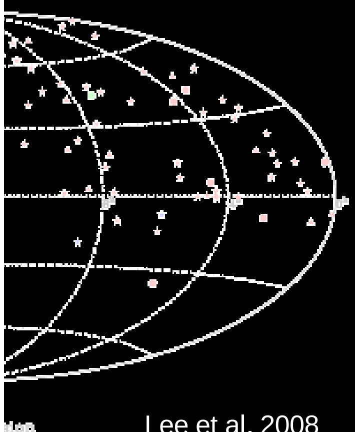
- Number of VLBI sources at mm-wavelengths are still very limited
  - more th
    while ~1 m



VLBA Cal Survey
Beasely et al. 2002

R





Lee et al. 2008

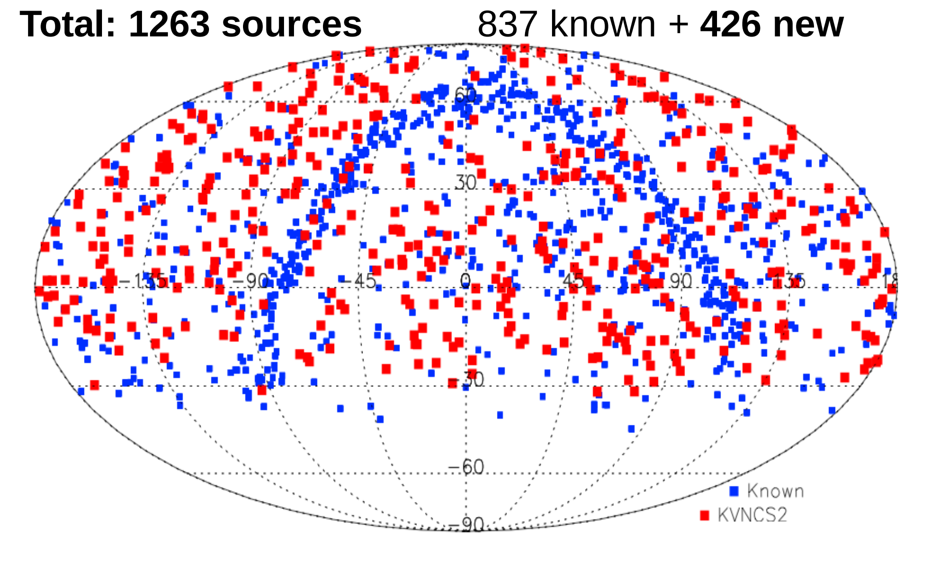
3414 s

3 mm

- Non-thermal
- 15~20% of AGNs are radio-loud while others are mostly radio-quiet
- FPT can extend the coherence time significantly

Multifrequency AGN Survey with the KVN

Discovering high-frequency sources & Maximizing uniqueness of the KVN

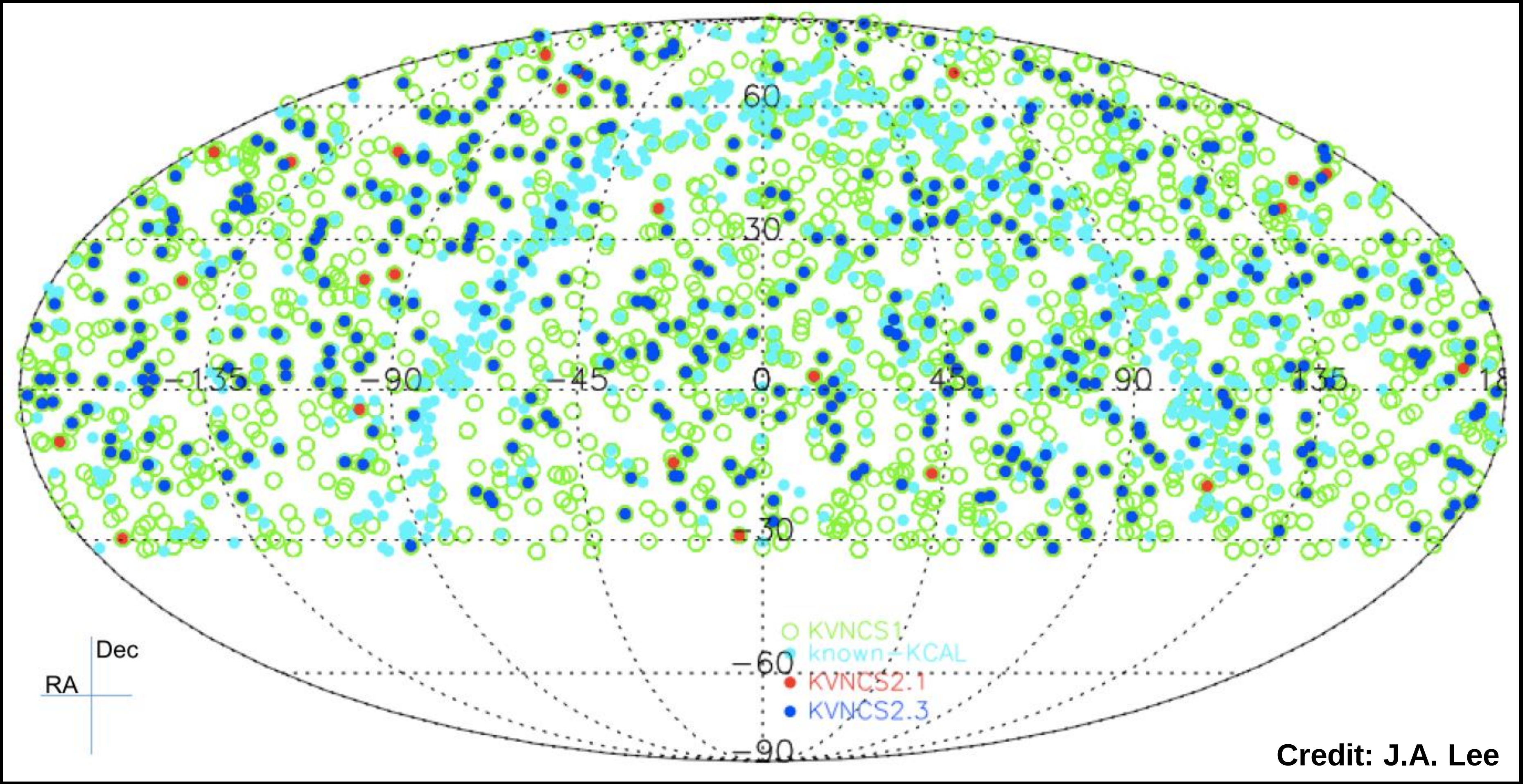


KVN Calibrator Survey (22/43GHz) by J.A. Lee

Multi-frequency source catalogue of selected samples

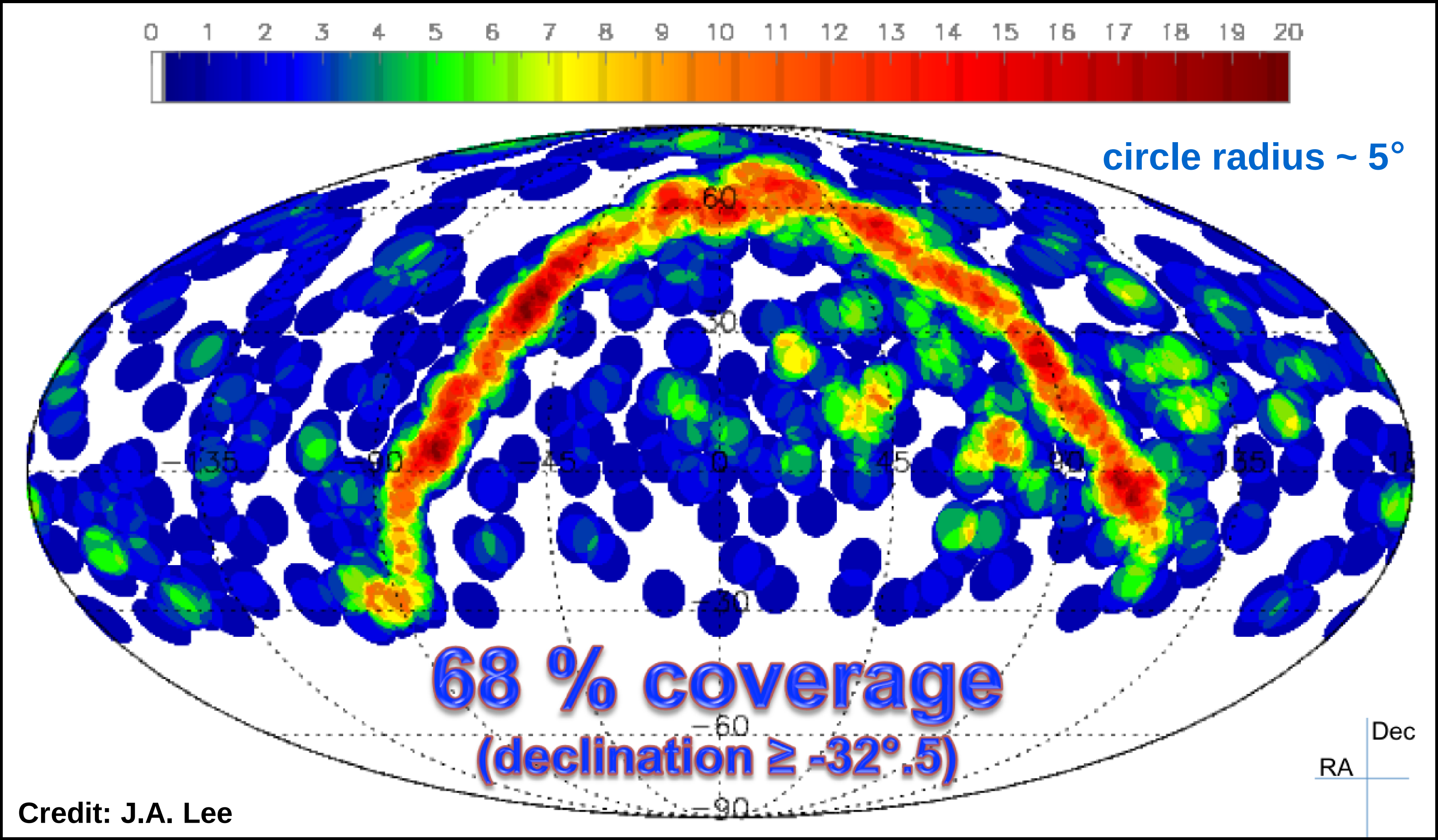
- Physical properties at 2-13mm wavelengths
  - flux density, spectral index, compactness, populations etc.
- Provides high frequency VLBI calibrators

Spatial Distribution of K-band Sources



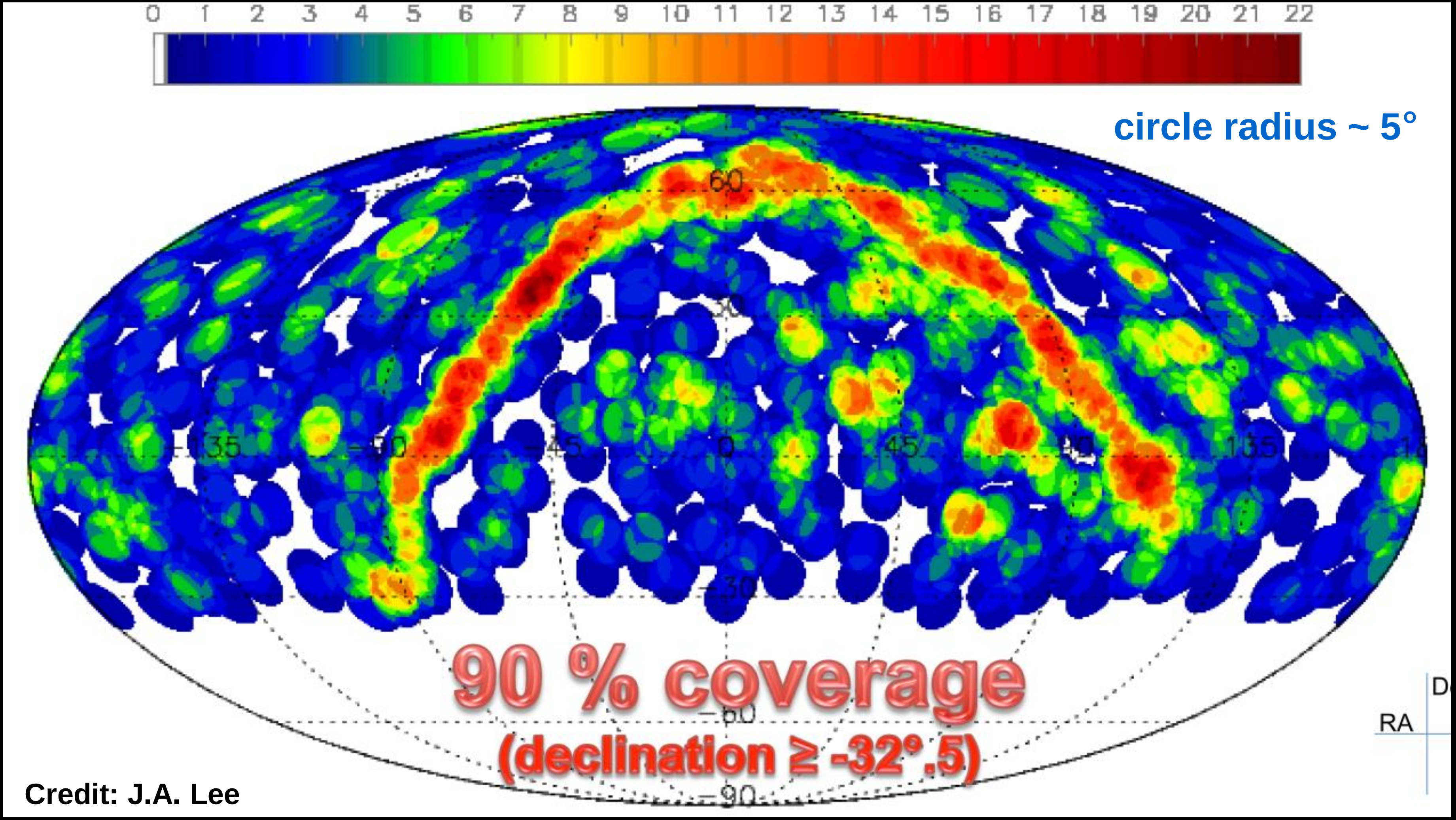
- KVNCS1: 1533 sources
- KVNCS2.1 & 2.3: 444 & 426 sources
- Known K-Cal : 837 sources

VLBI Calibrators at K-band (known 837 sources)



- **837 known sources**
  from VERA (Petrov+07), ICRF-K (Lanyi+10), VGaPS (Petrov+11), EGaPS (Petrov+12), KCAL (Petrov+12)

VLBI Calibrators at K-band
(known 837 sources + new 426 sources)



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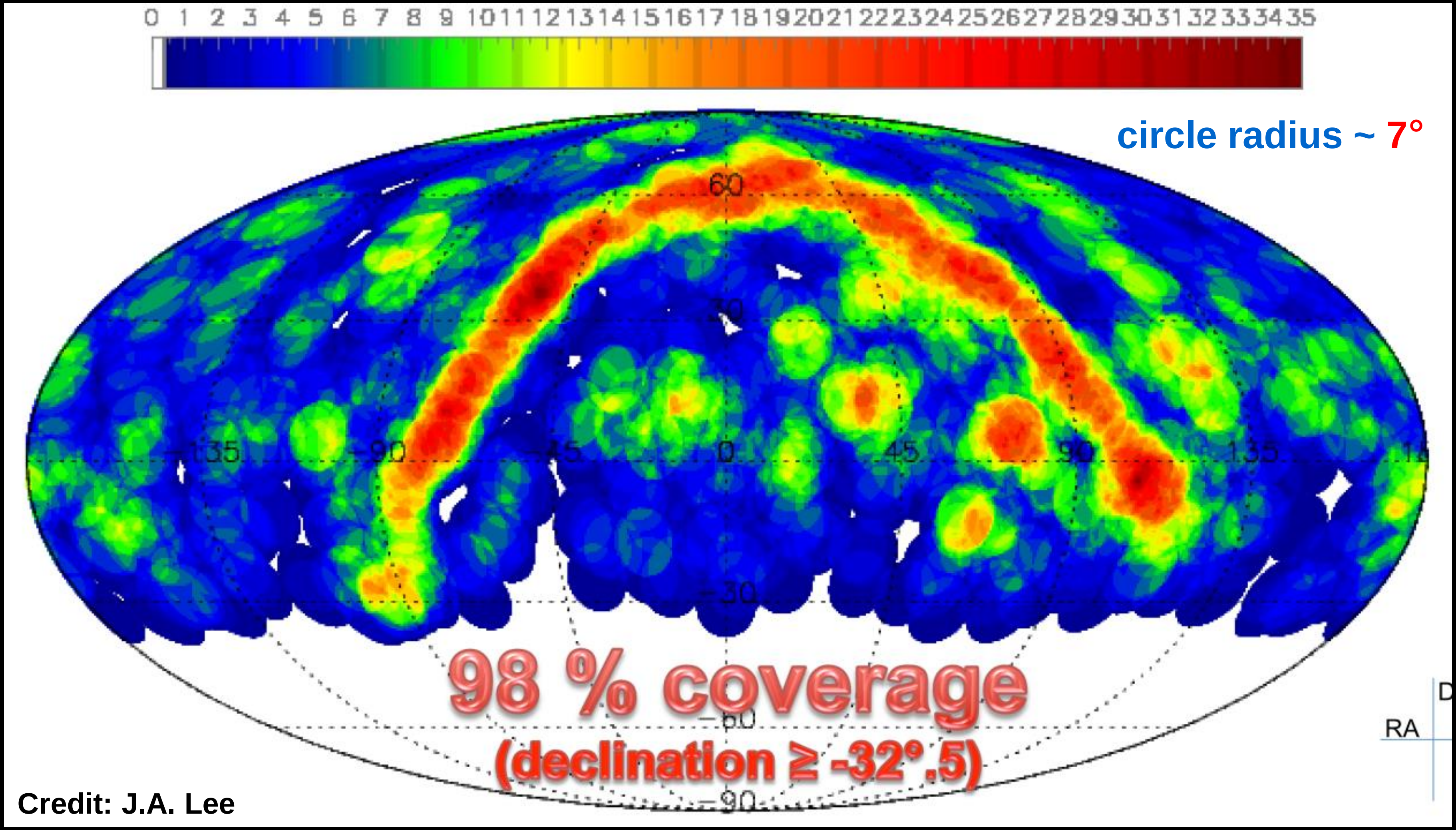
VLBI Calibrators at K-band
(known 837 sources + new 426 sources)



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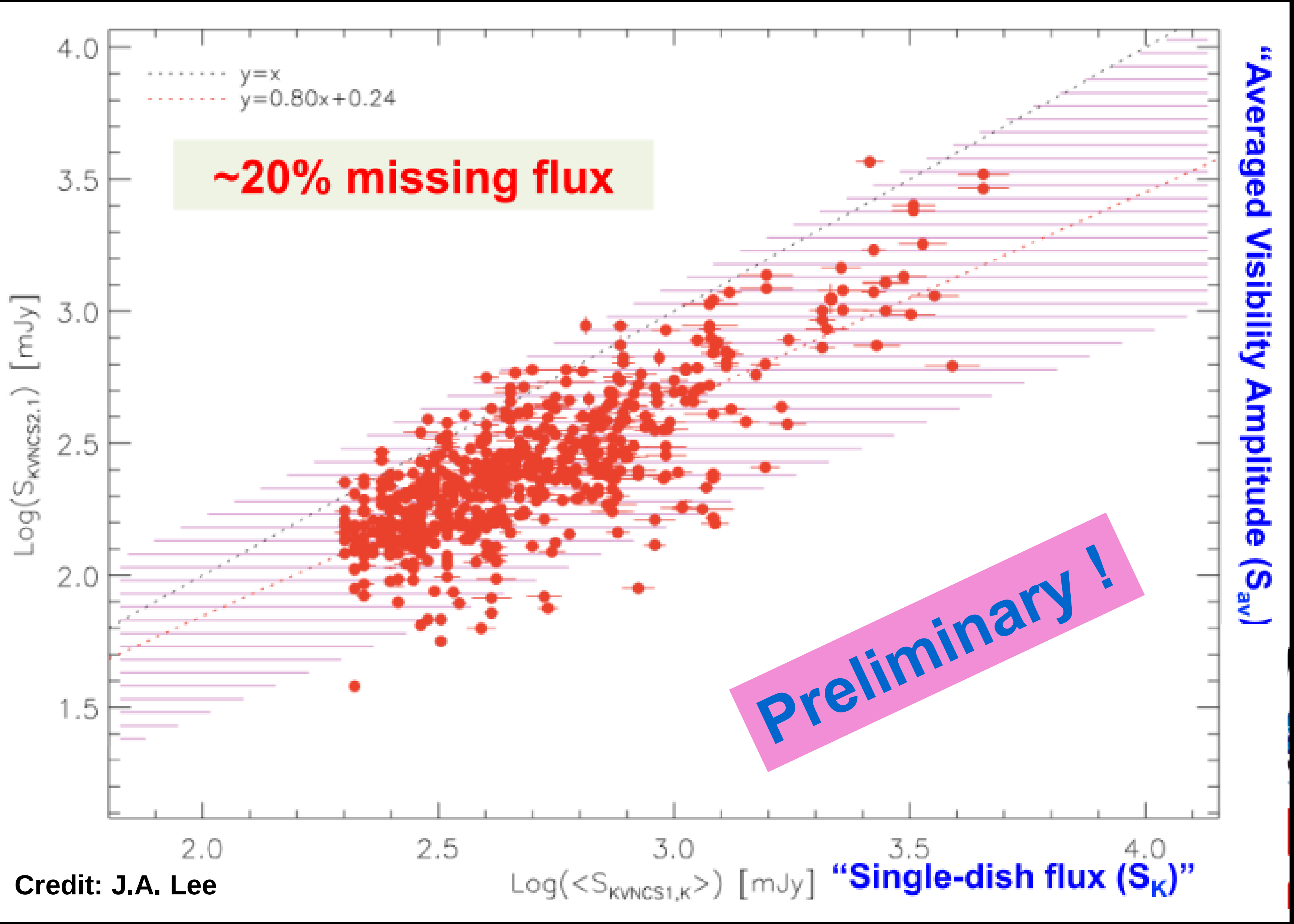
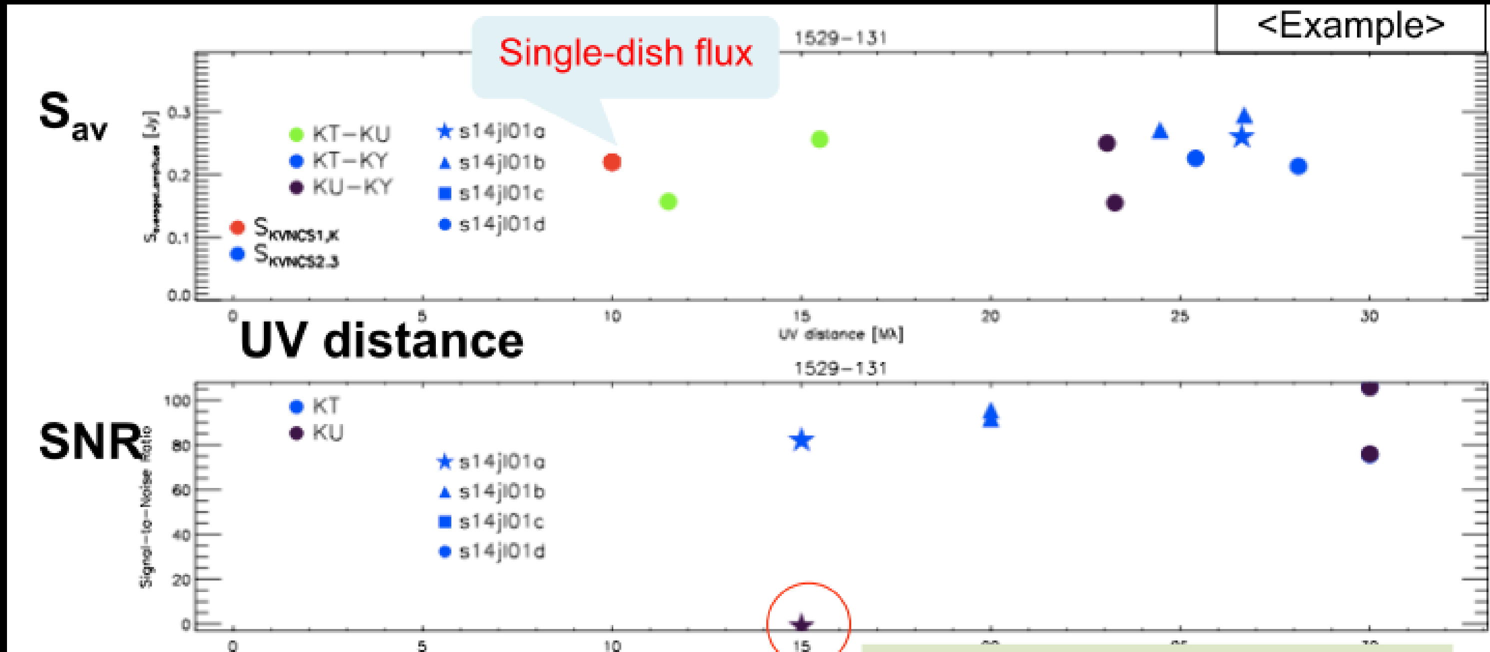
K-band Flux – Flux Relation: KVN Single vs. VLBI

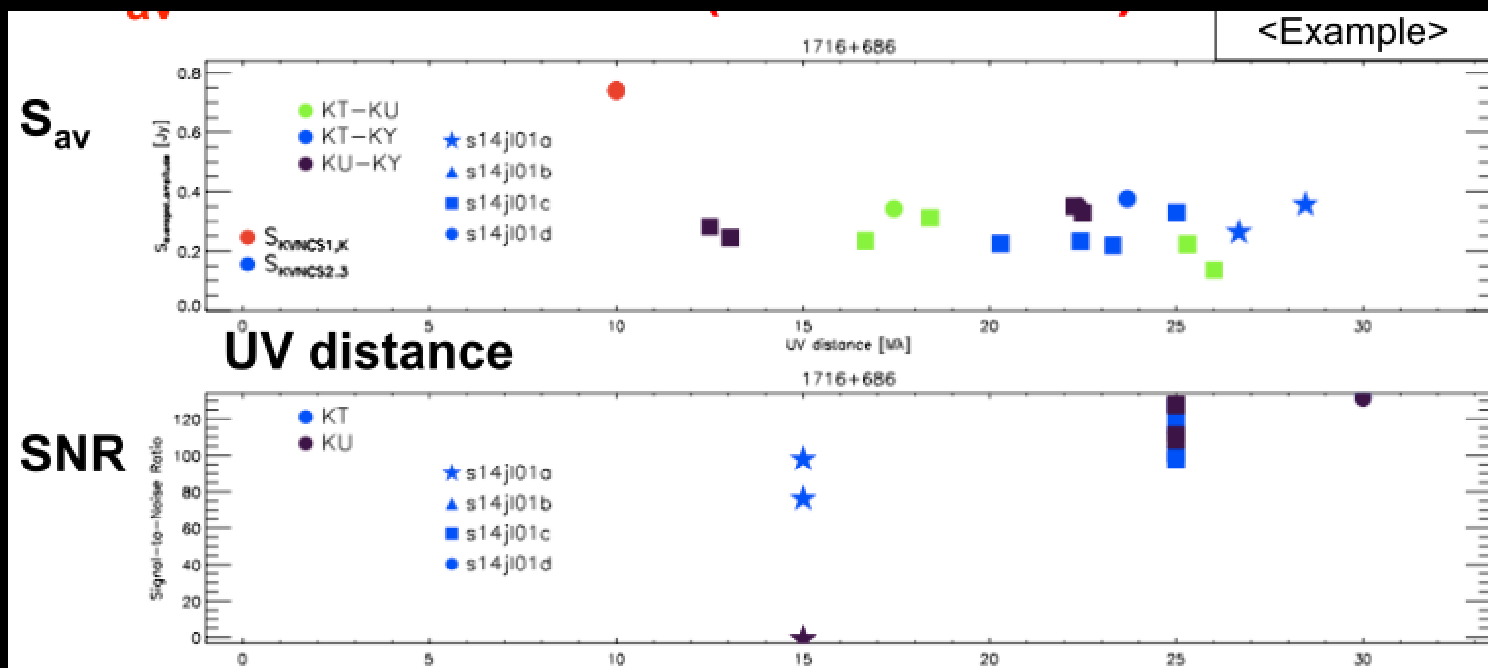


Credit: J.A. Lee

Examples



1529-131



1716+686

Expected Outcomes from MASK

- Simutlaneous Multi-Freuqency (22/43/86/129GHz) VLBI Source Catalog
  - Starting with 1263 sources
    Based on the K-band single dish detection (flux limit > 200 mJy)
    Most of sources can be detected at K-band SNR > 10
    by assuming 20% flux loss, 30sec integration
  - Simultaneous Multi-frequency Spectal Information
    Unique information of high frequency VLBI sources
  - Statistical Study
    - flux limited samples (based on K-band detection)
    - volume limited samples (according to the redshift)
    - multi-band / multi-wavelength spectra
      - 20 GHz ~ 130 GHz, (1.4 ~ 20 GHz, archive)
      - X-ray / optical / IR / radio
  - High frequency astrometry (ICRF, GAIA, Coreshift)

Pilot MASK Observation

- Source sample : Non-detection SRCs at 86GHz with 1Gbps
- Four observation have been made (total 123 sources)
  One obs. was failed due to the weather (36 sources was removed)
  Total 87 sources are analyzed

Epoch	baseline	43GHz	86GHz	129GHz	Tsys@129GHz
1st	KU-KT	20	9	0	KY: 200 ~1000 KU: 180~1000 KT: 100~600
	KU-KY	20	10	4	
2nd	KU-KT	13	0	0	KY: 300 ~1000 KU: 250~5000 KT: 300~5000
	KU-KY	13	2	0	
3rd	KU-KT	1	2	0	KY: 600 ~4000 KU: 200~5000 KT: 200~5000
	KU-KY	2	2	0	
Total	# of detection	35/87 ~40%	14/87 ~16%	4/87 ~5%	

- Although these samples are extreme case (non-detected at 86GHz with 1Gbps mode), Applying FPT results in 14 sources detection at 86 GHz including 4 source detection at 129GHz (40% of 86GHz detection).

Strategy for MASK (planning)

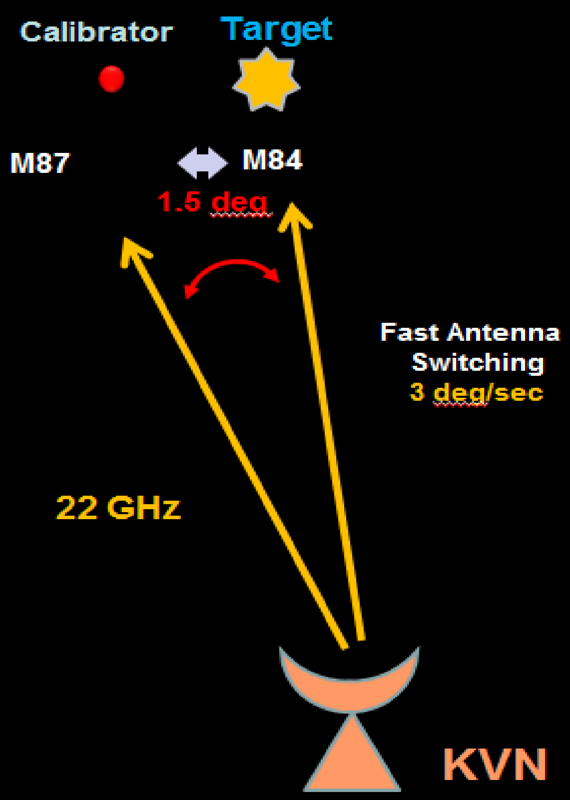
- 1st Survey (2015B winter ~ 2016A)
  - Target ~ 1200 sources at K-band
  - 1 Gbps (64Mhz / band)
  - dynamic scheduling (no harms to existing observation)
  - pipelining (ParselTongue)
  - spectral index (compactness)
  - select priority of samples (design)
  - criteria can be provided for the 2nd survey

- 2nd Survey (2016B~)
  - 8Gbps mode (2Gbps per band)
  - 4CH astrometry (wideband & Pcal)

For Precise Astrometry in mm-VLBI

KVN Activities

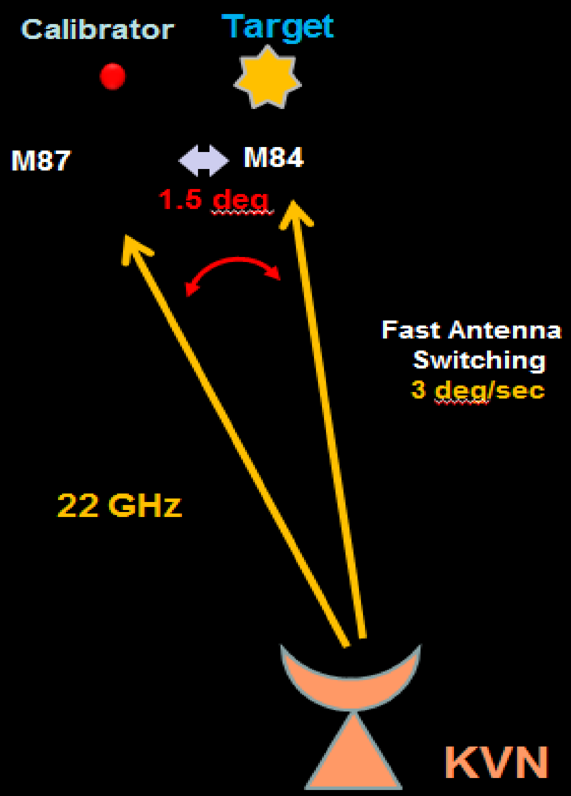
KVN Phase Referencing Test



- Observing Frequency : 22/43/86/129 GHz
- Bandwidth : 64MHz per each frequency
- Observation configuration :
  - conventional phase referencing (fast antenna switching btw. target & calibrator) with multi-frequency simultaneous observation
  - switching cycle : ~ 1 minutes
  - on source time per scan : 18~25 sec for each
- Source Pairs (separation angle, * calibrator)
  1. M87* - M84 (1.5 deg)
  2. J1222+0413* – NGC4261 (1.8 deg)
  3. 3C273* – 3C279* (10.4 deg)

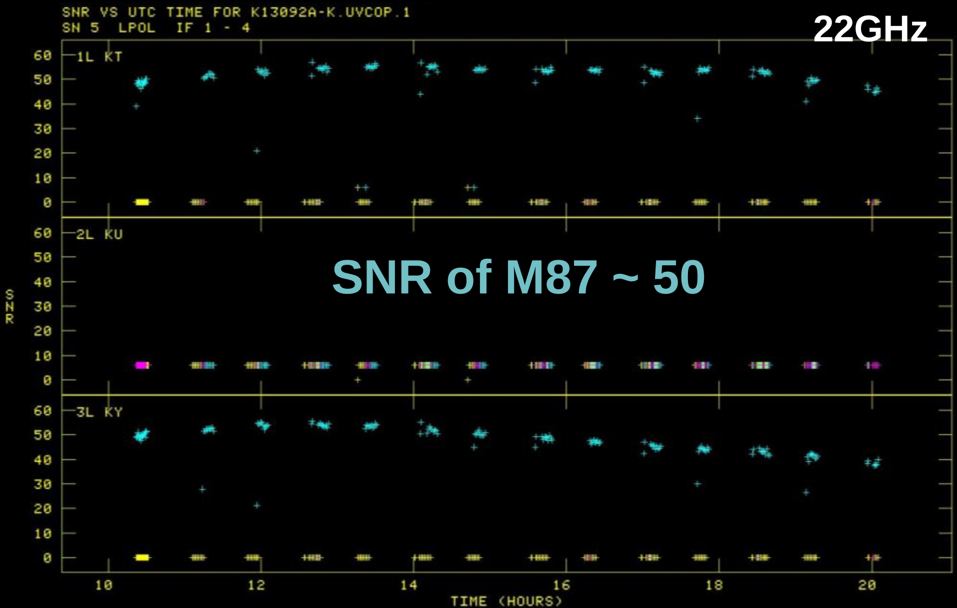
Three Phase Referencing Methods in KVN

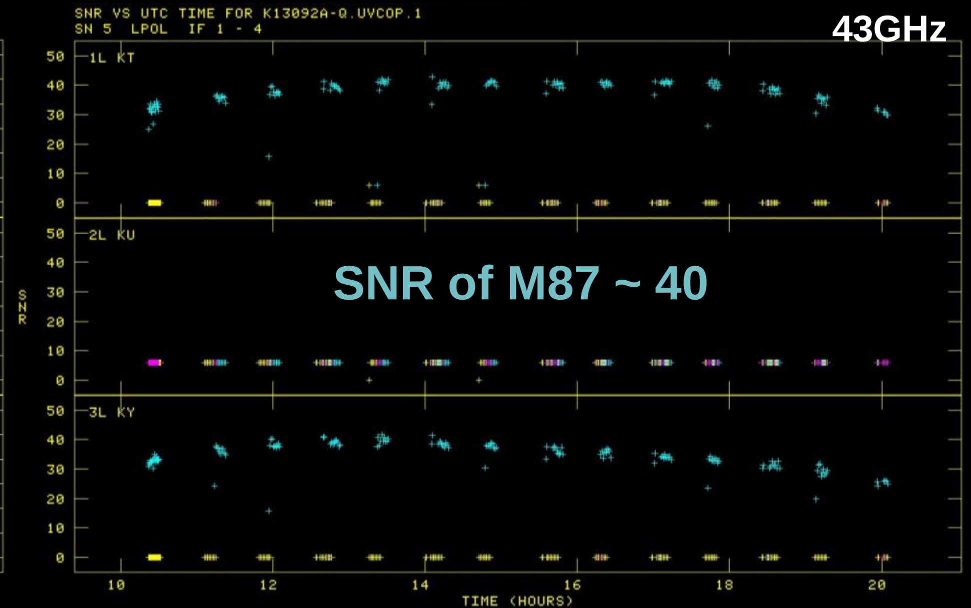
FAS conventional PR

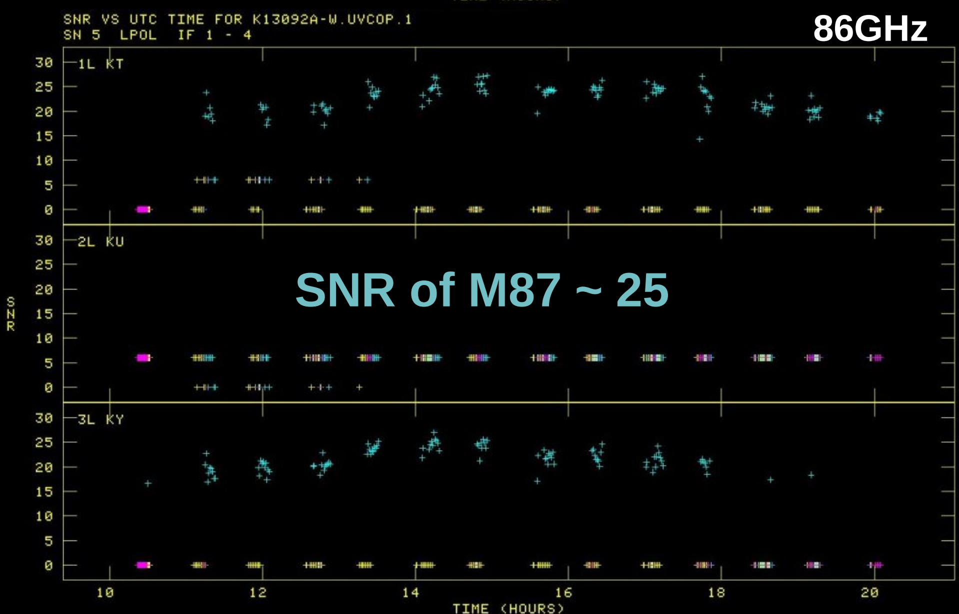


SNR: M87-M84

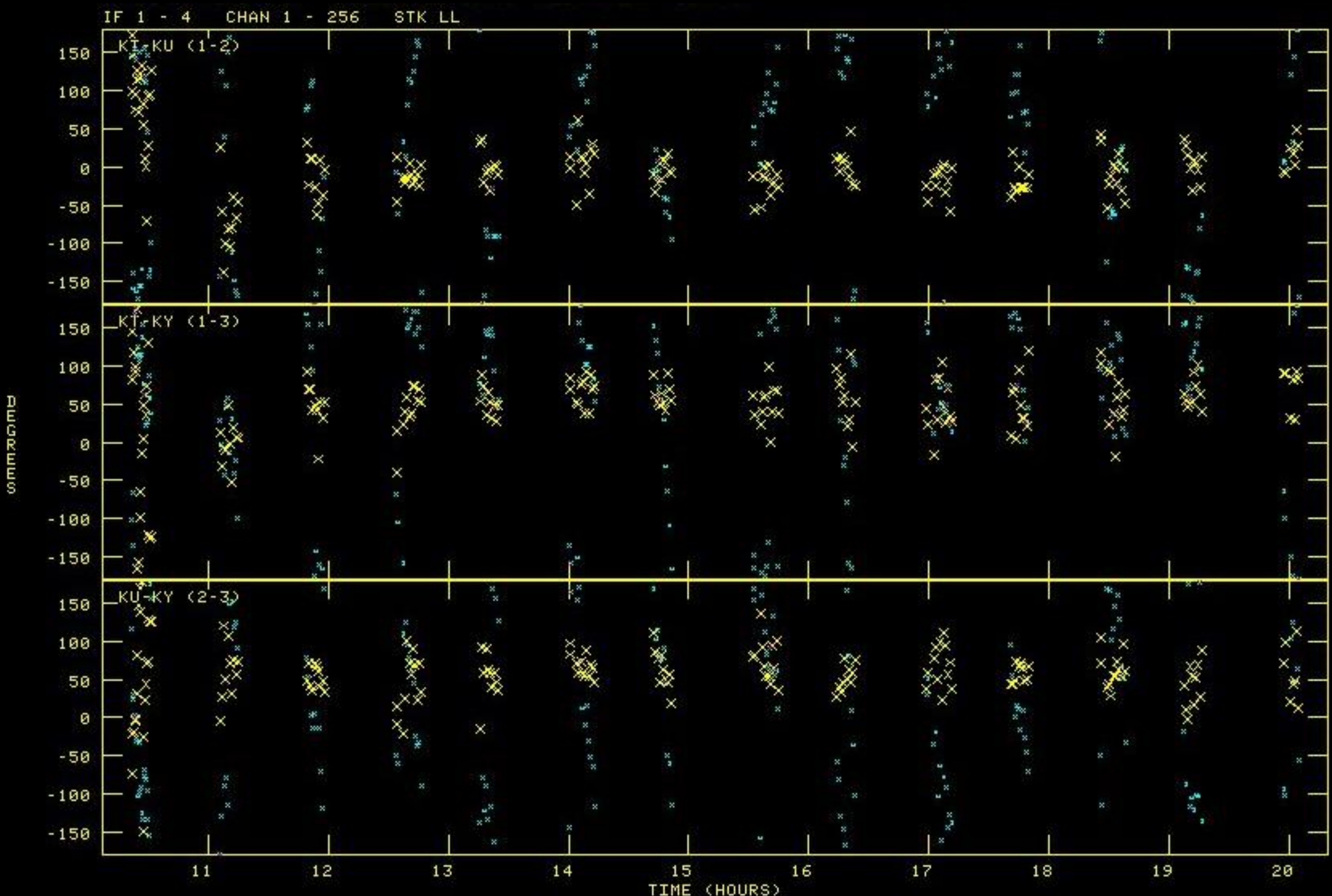
M84 – no detection at all freq.

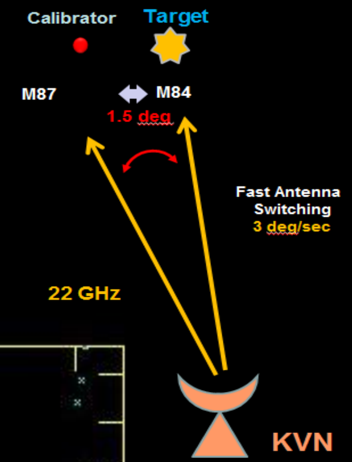




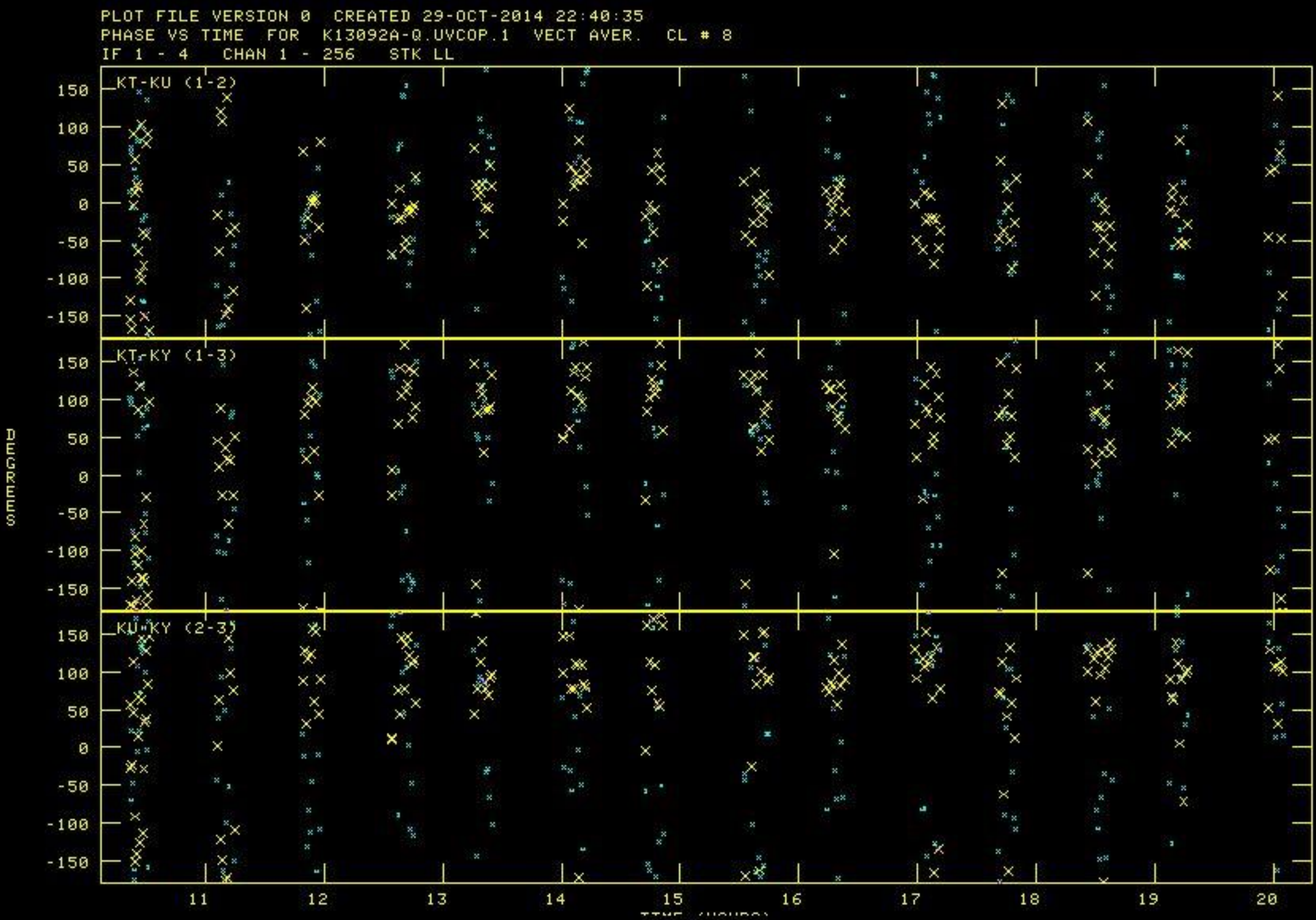


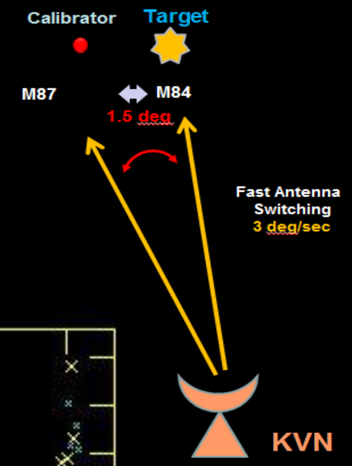
Fast Antenna Switching Phase Referencing
M87-M84 Test at 22GHz



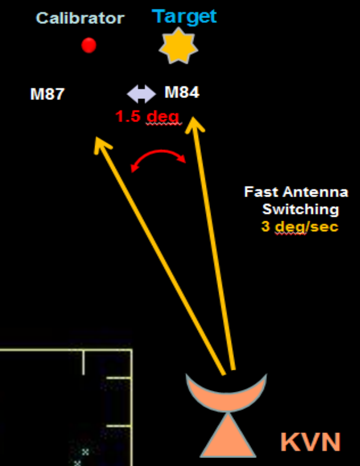


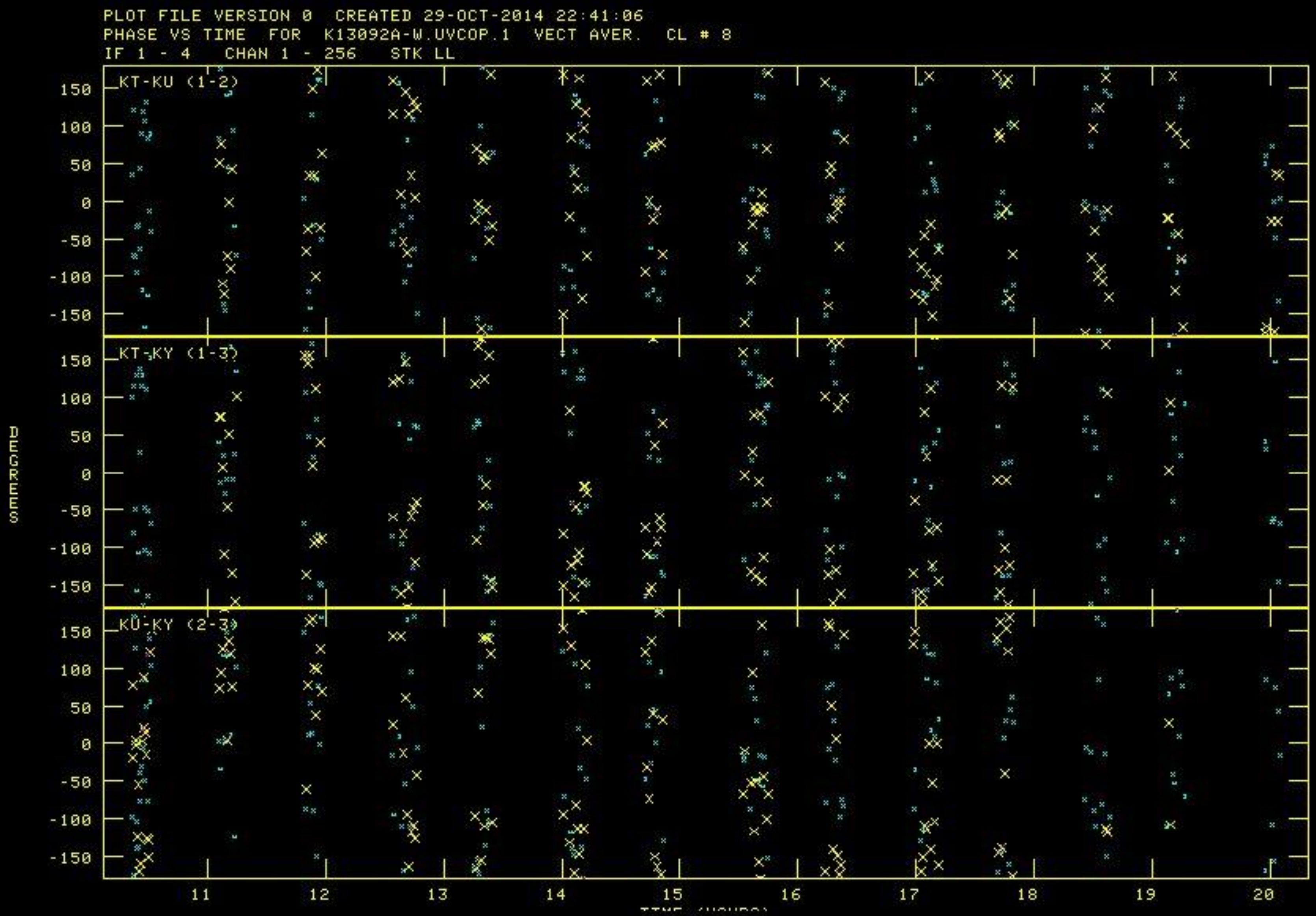
Fast Antenna Switching Phase Referencing M87-M84 Test at 43GHz



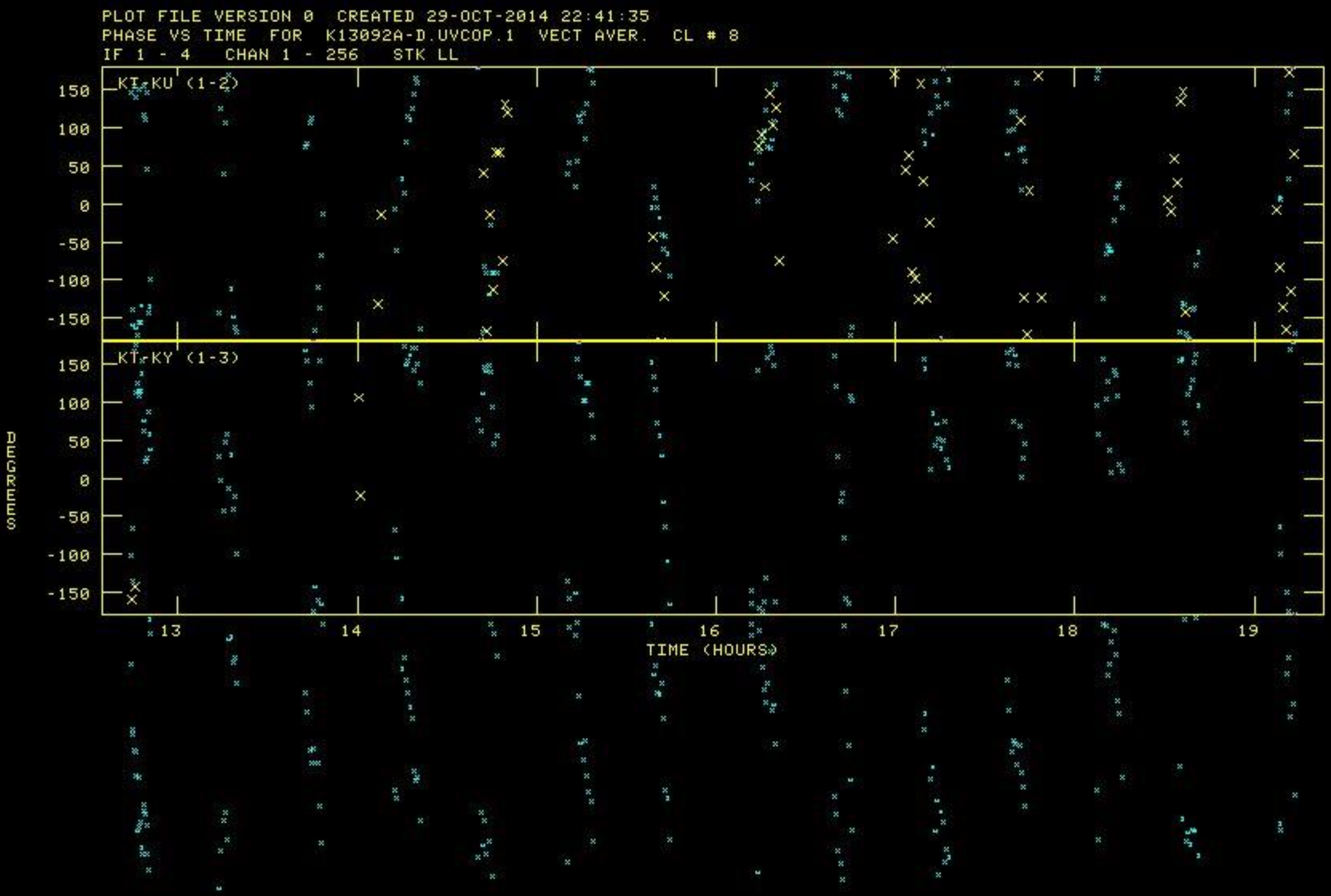


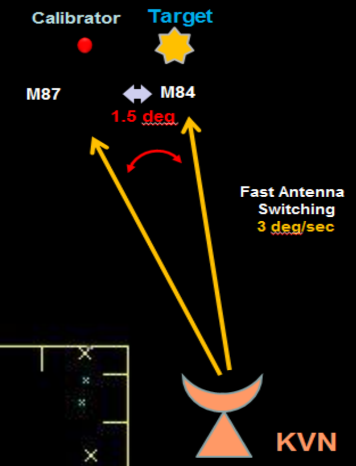
Fast Antenna Switching Phase Referencing
M87-M84 Test at 86GHz





Fast Antenna Switching Phase Referencing
M87-M84 Test at 129Ghz

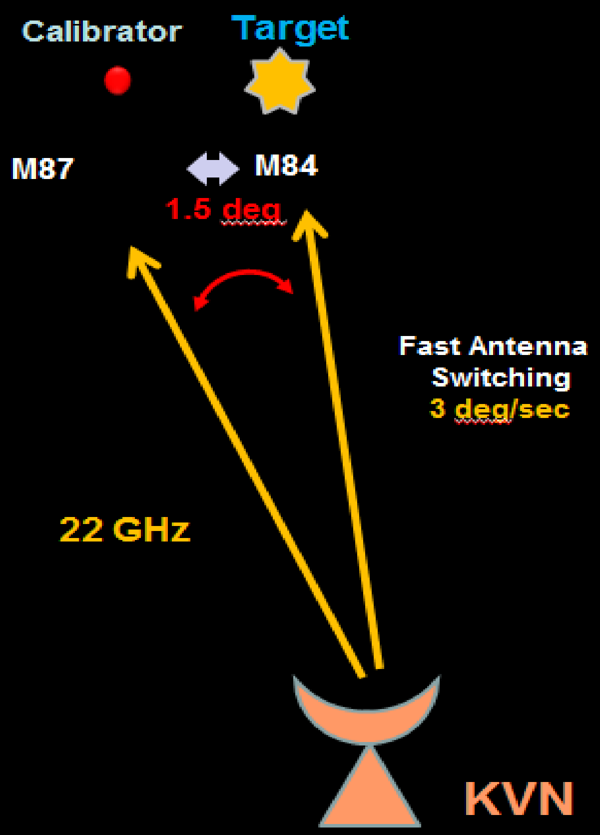


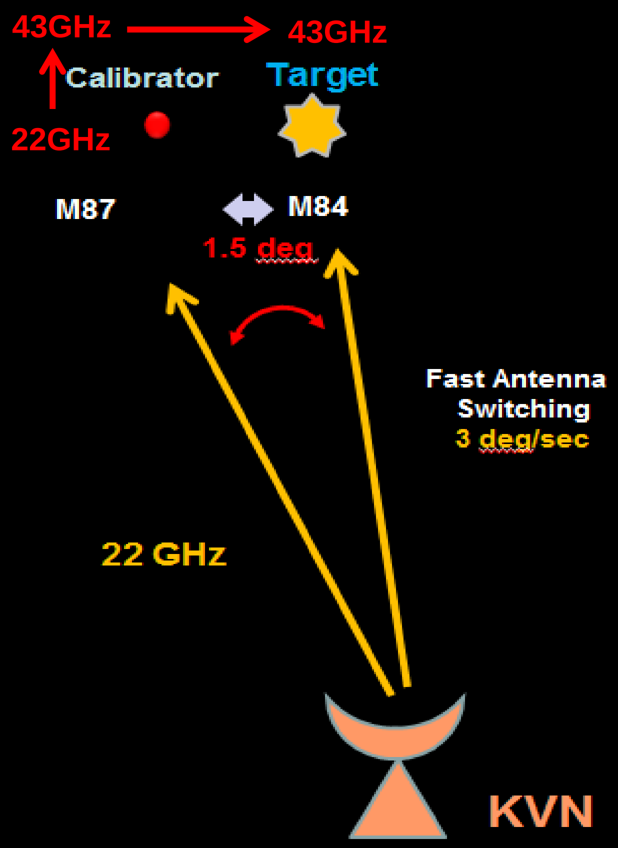


Three Phase Referencing Methods in KVN

FAS conventional PR

FPT + FAS
1. phase scaling of calibrator
2. apply conventional PR



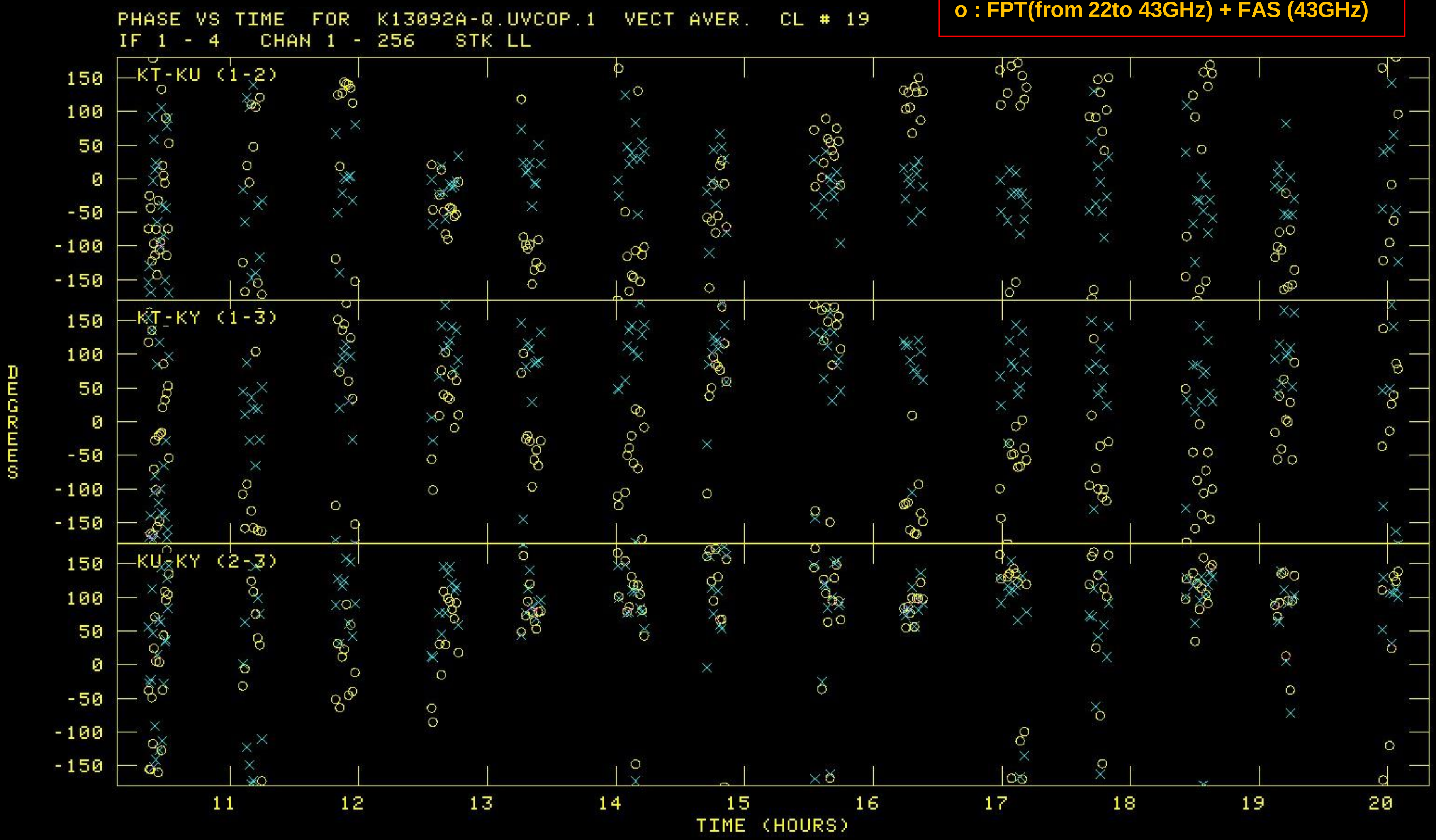


Example : FAS vs (FPT+FAS) : M84 calibrated by M87

FPT + FAS

1. phase scaling of calibrator
2. apply conventional PR

x : 43GHz FAS phase
o : FPT(from 22to 43GHz) + FAS (43GHz)



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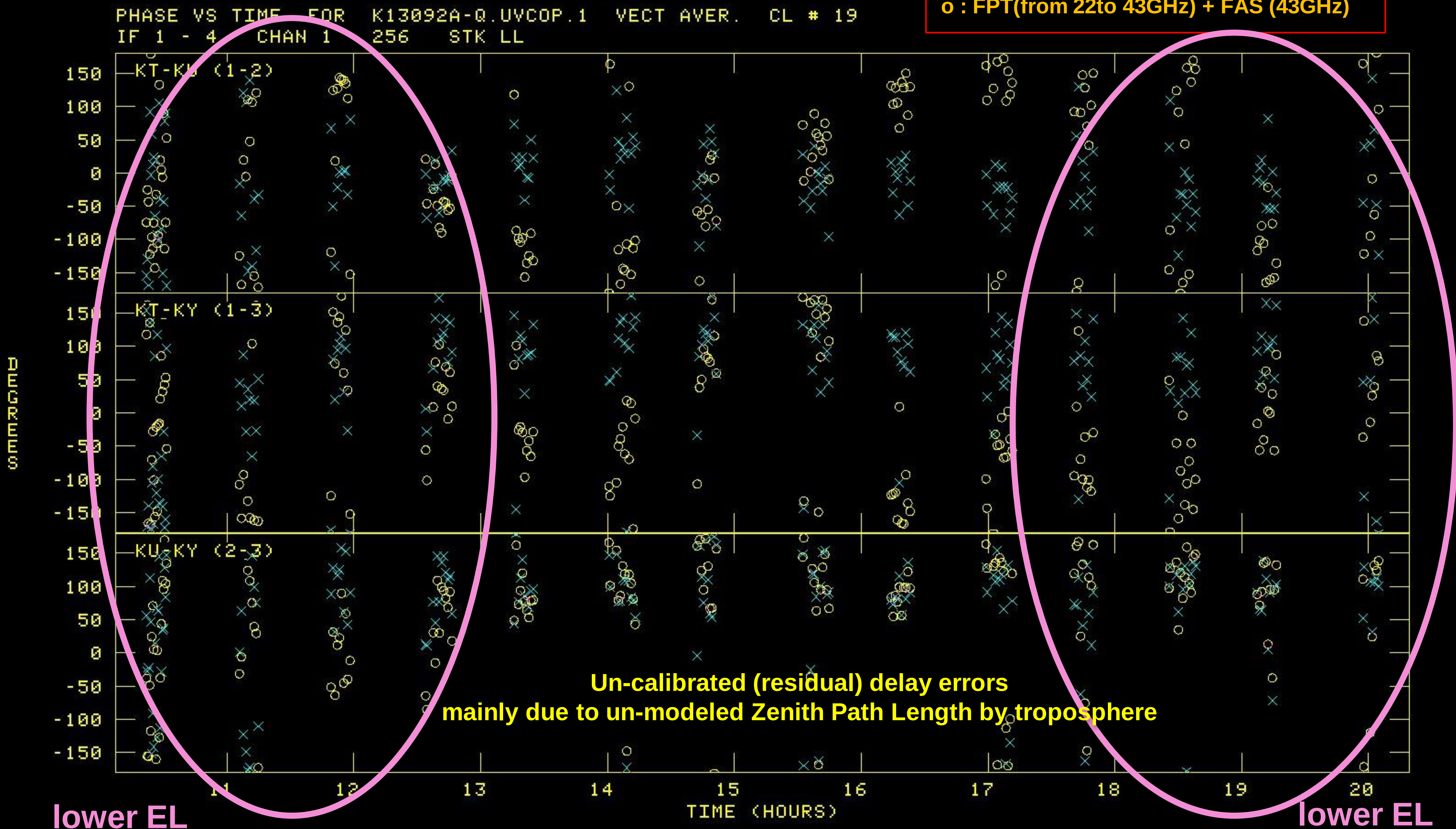
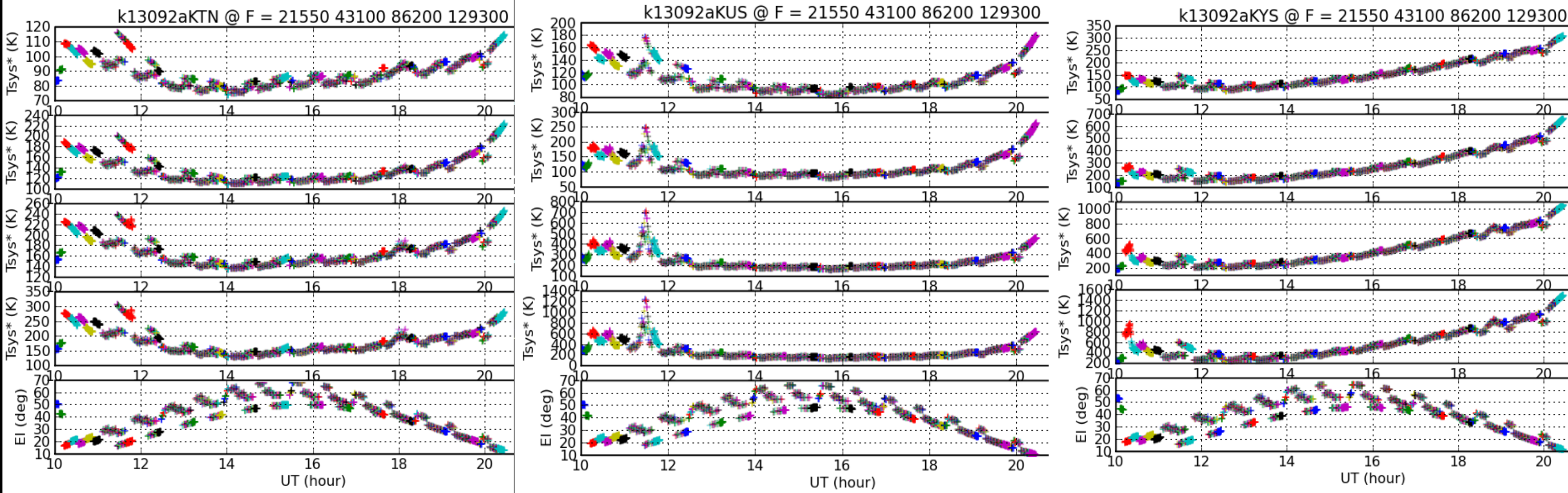
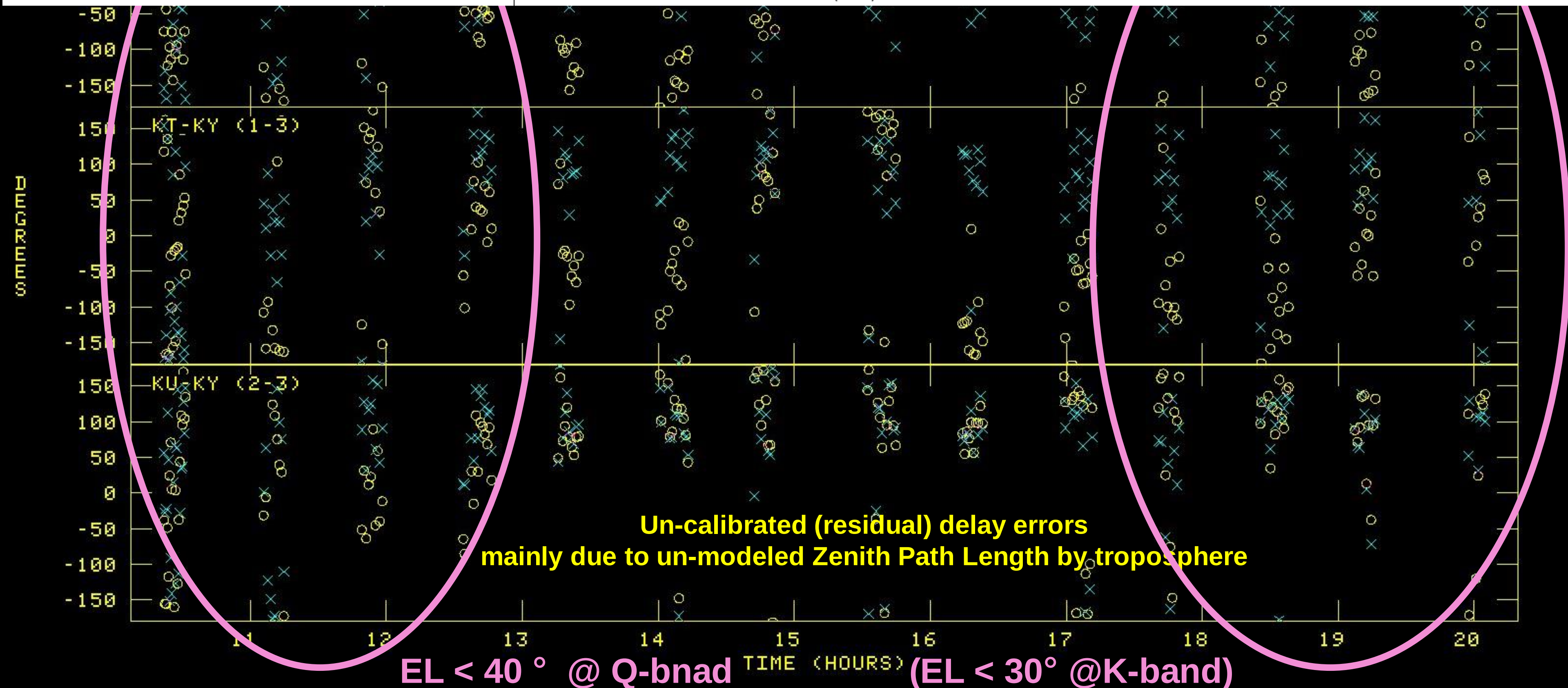




k13092aKTN @ F = 21550 43100 86200 129300
k13092aKUS @ F = 21550 43100 86200 129300
k13092aKYS @ F = 21550 43100 86200 129300
Tsys* (K)
El (deg)
UT (hour)

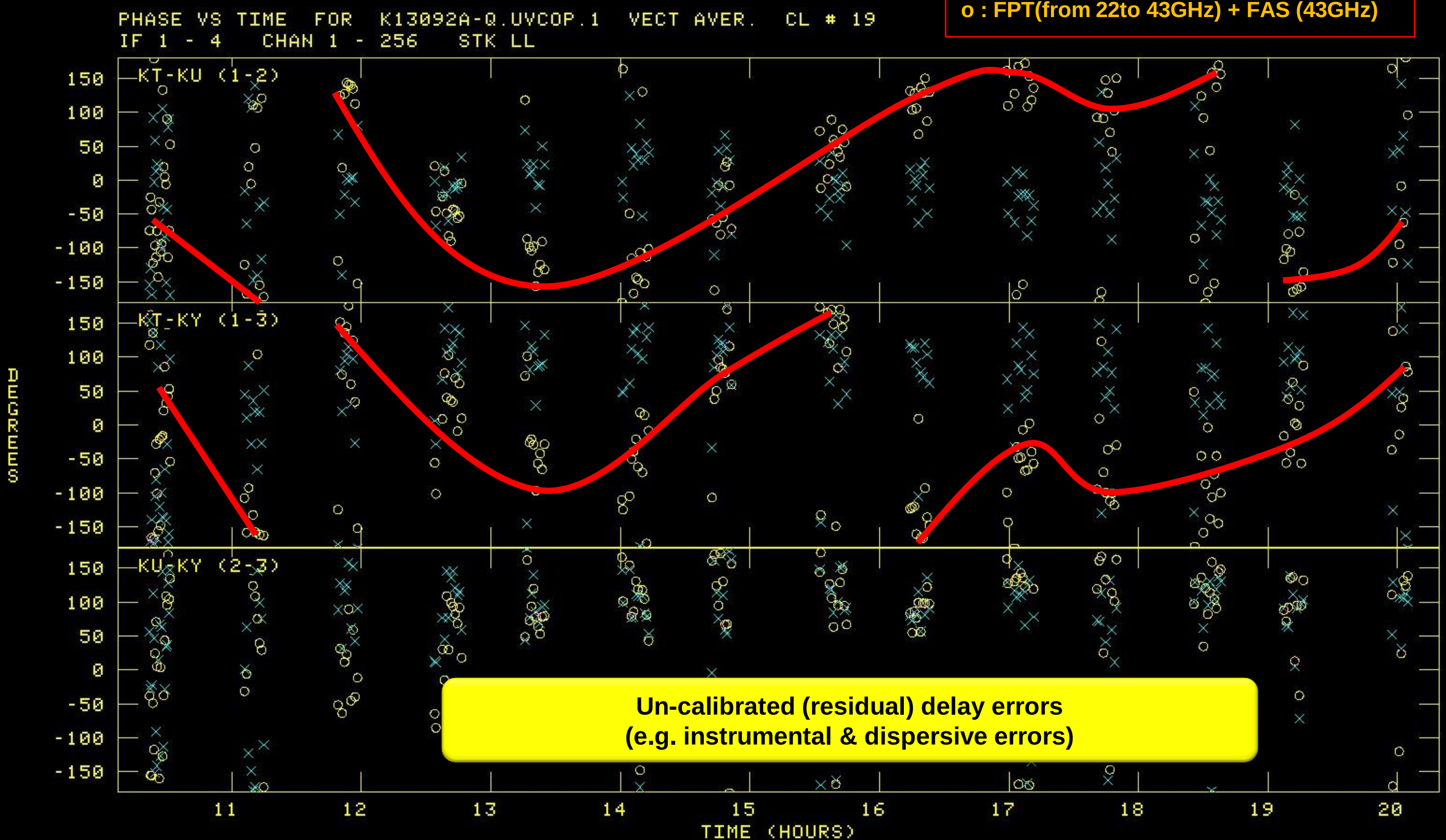


DEGREES
KT-KY (1-3)
KU-KY (2-3)
TIME (HOURS)
Un-calibrated (residual) delay errors
mainly due to un-modeled Zenith Path Length by troposphere
EL < 40 ° @ Q-bnad
(EL < 30° @K-band)

Example : FAS vs (FPT+FAS) : M84 calibrated by M87

FPT + FAS
1. phase scaling of calibrator
2. apply conventional PR

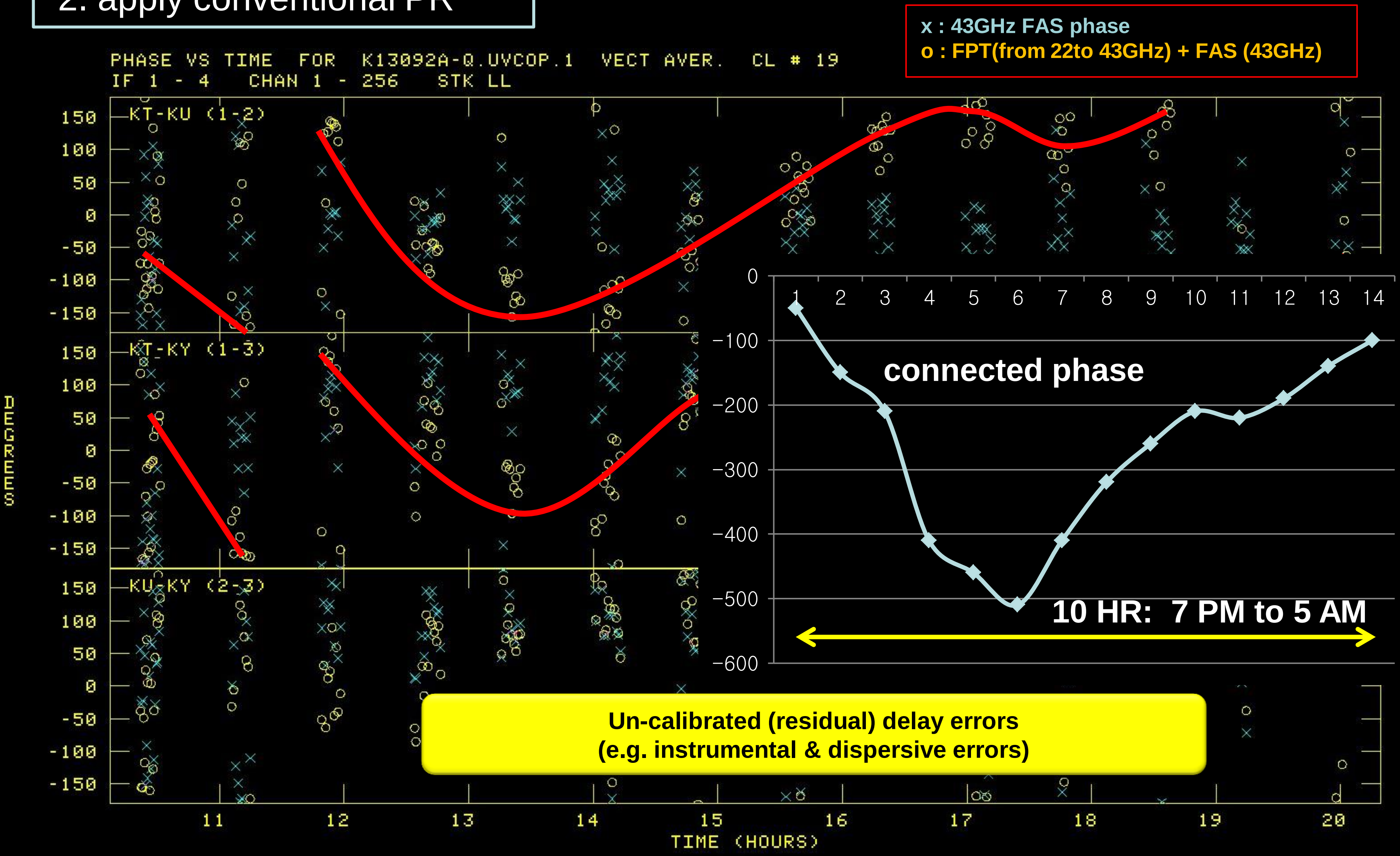
x : 43GHz FAS phase
o : FPT(from 22to 43GHz) + FAS (43GHz)



Example : FAS vs (FPT+FAS) : M84 calibrated by M87

FPT + FAS

1. phase scaling of calibrator
2. apply conventional PR

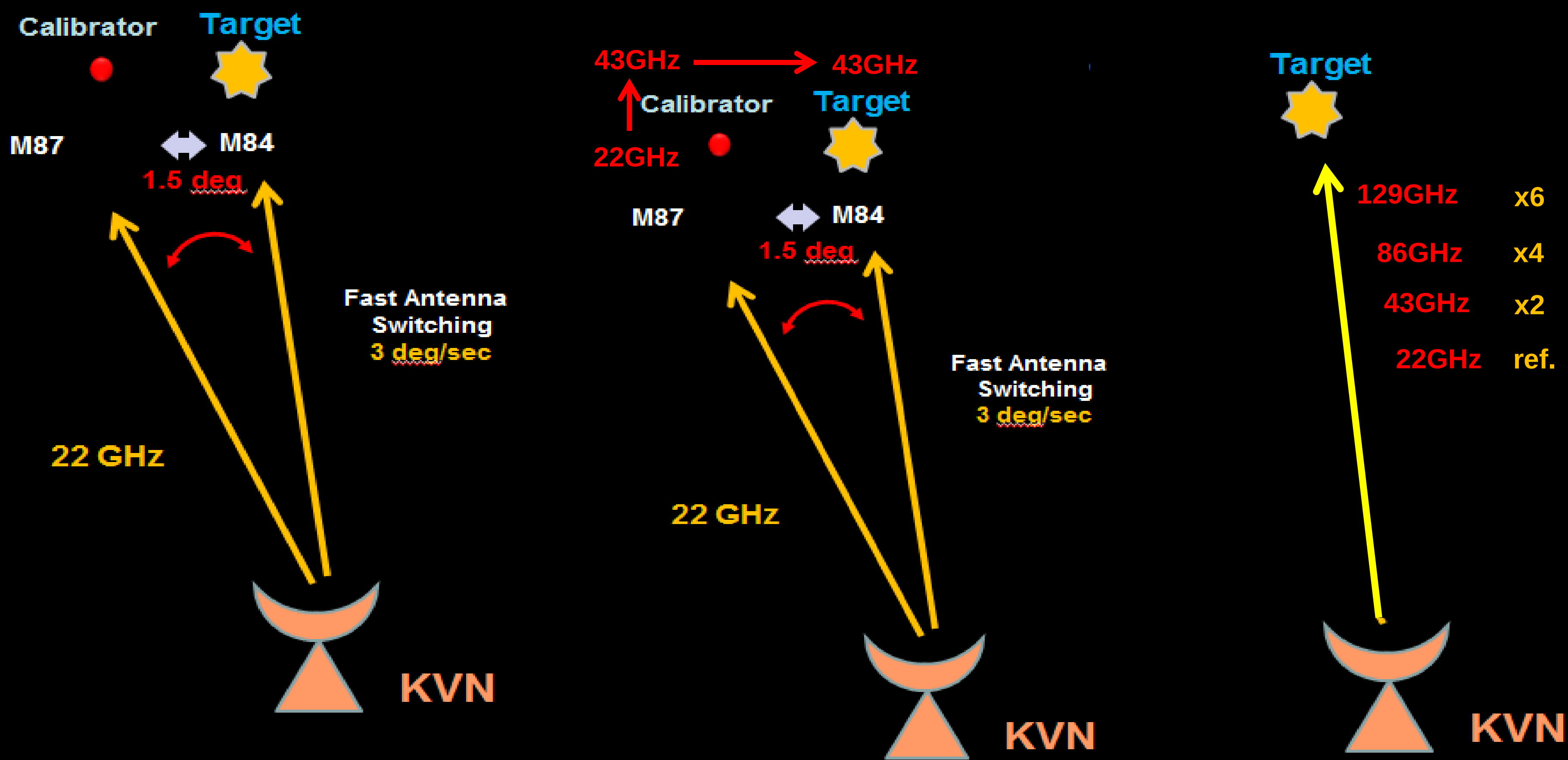


Three Phase Referencing Methods in KVN

FAS conventional PR

FPT + FAS
1. phase scaling of calibrator
2. apply conventional PR

FPT
Frequency Phase Transfer

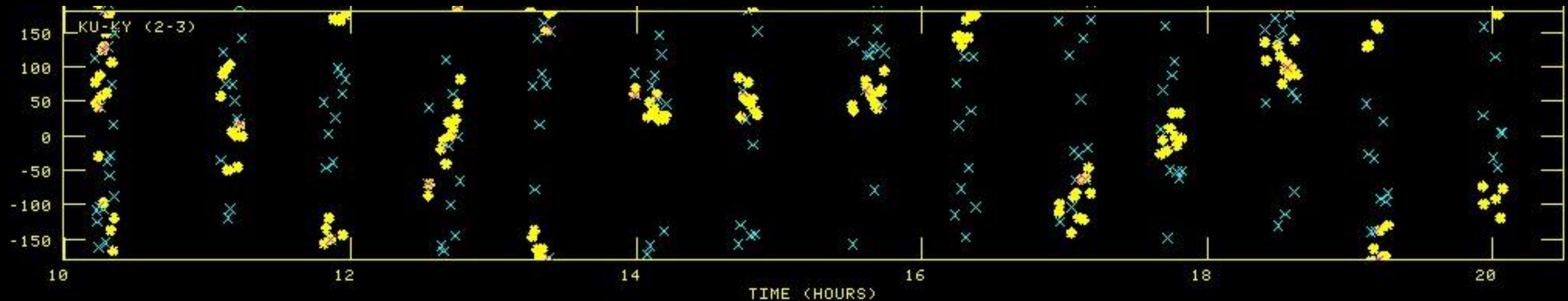


Comparison: Raw Visibility Phase & FPT Phase for M87

43GHz Raw & FPT (22GHz phase x 2)

86GHz Raw & FPT (22GHz phase x 4)

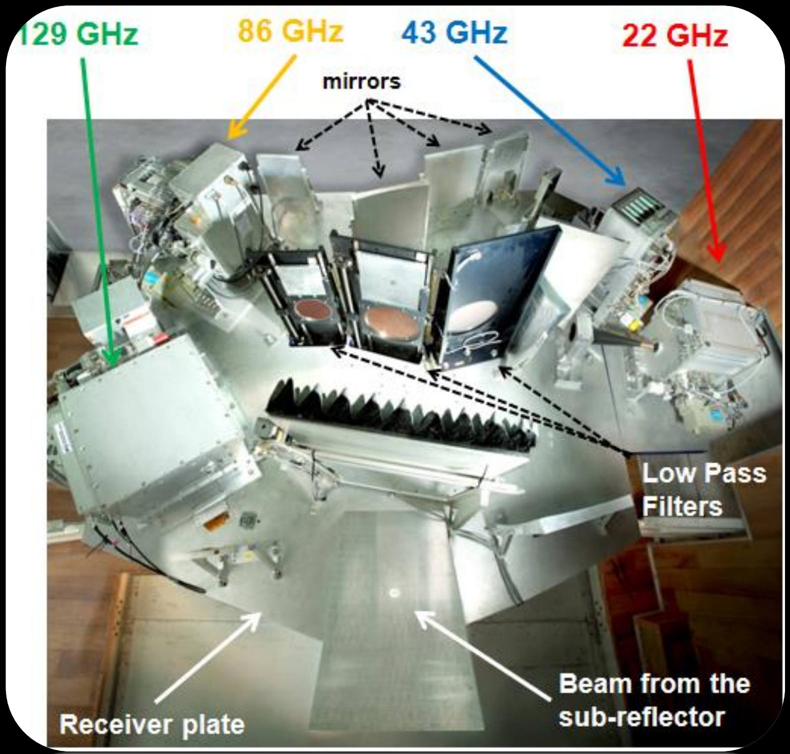
129GHz Raw & FPT (22GHz phase x 6)



Pcal & GPS System

High Precision Astrometry

Implementation of "Phase Calibration System"



- Fringe phase should be coherent across the entire set of channels produced by each "IF" in KVN

- It can correct phase offsets between the "IFs"

- It measures changes in the delays through the cables and electronics which must be removed for accurate geodetic and astrometric observations

- The tones injected in to the signal path at the receivers (QO systems) serve to define the delay reference point for astrometry!
  ➔ KVN (independent) 4CH-Rx System as a "Single Unified 4CH-Rx System"

- True "Multi-Freuqency Phase Refeerncing"

- Applications
  - Amplitude calibraiton: Tsys ~ 1/ (pcal-amp)^2
  - Benefits on Polarimetry
  - Multi-Frequency Synthesis

Frequency Phase Transfer (FPT)

calibrated by P-cal system

$$\Phi^h = \Phi^h{}_{str} + 2\pi\nu^h(\tau_g + \tau_C + \tau_{inst} + \tau_{trop} + \tau_{ion}) + \Phi^h{}_{LO}$$

$$\Phi^l = \Phi^l{}_{str} + 2\pi\nu^l(\tau_g + \tau_C + \tau_{inst} + \tau_{trop} + \tau_{ion}) + \Phi^l{}_{LO}$$

Self-calibration at lower frequency

$$\Phi^l{}_{str}$$

$$2\pi\nu^l(\tau_g + \tau_C + \tau_{inst} + \tau_{trop} + \tau_{ion}) + \Phi^l{}_{LO}$$

$$\Delta\Phi = \Phi^h - r\Phi^l$$

$$r = \nu_h / \nu_l$$

slow varying term

$$\Delta\Phi = \Phi_h - \frac{\nu_h}{\nu_l}\Phi_l = \Phi_h{}^{str} + 2\pi\nu_h(\tau_h{}^g - \tau^g{}_l) - 2\pi\left(1 - \frac{\nu_h^2}{\nu_l^2}\right)\frac{\nu_0^2}{\nu_h^2}\tau^{ion} + (\Phi_h{}^{LO} - \frac{\nu_h}{\nu_l}\Phi_l{}^{LO})$$

Source Structure

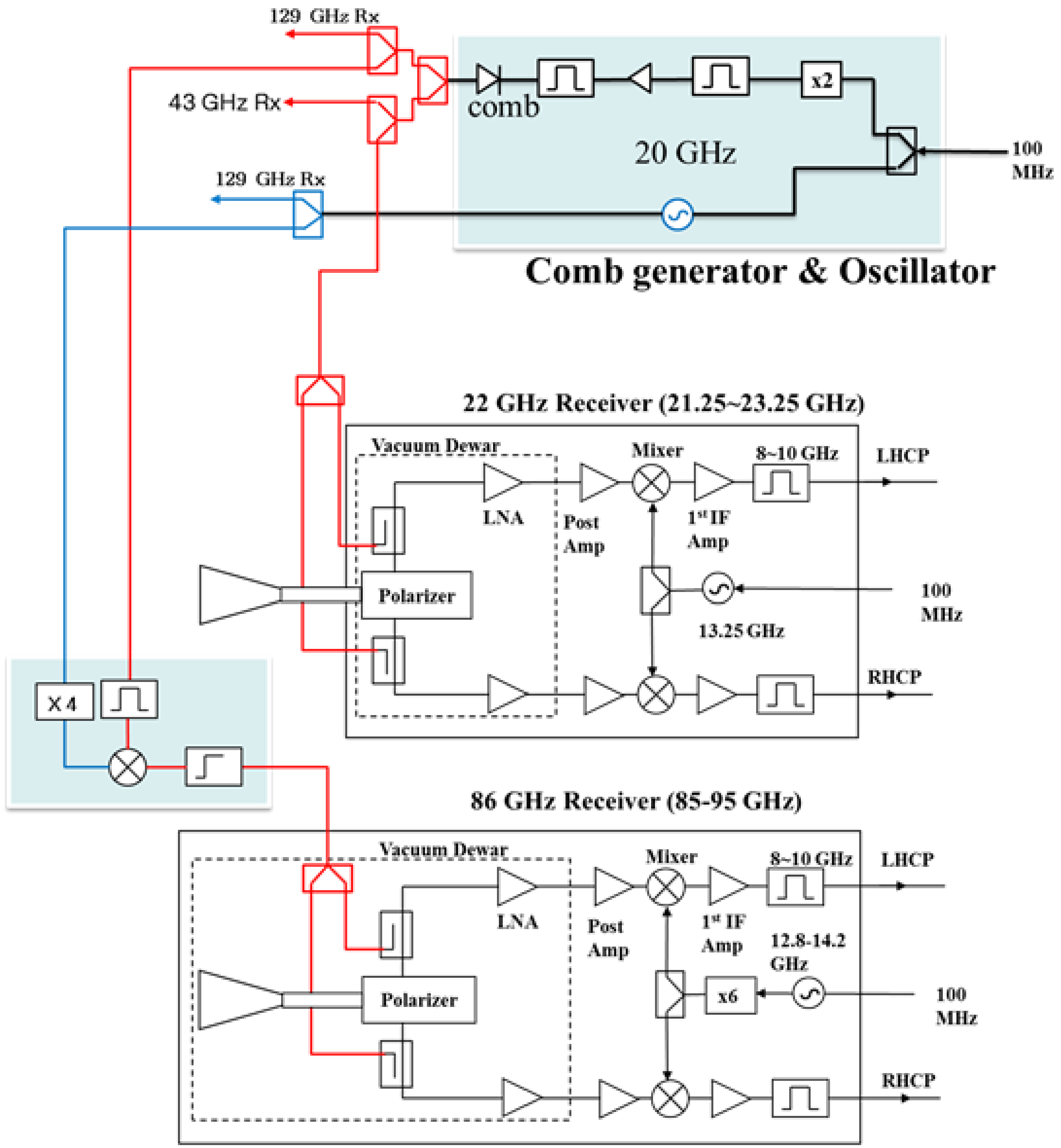
geometric difference

ionosphere

instrument

By doing Self-calibration again for longer solution interval,
we can get an image at higher frequency

Design of KVN Pcal-System



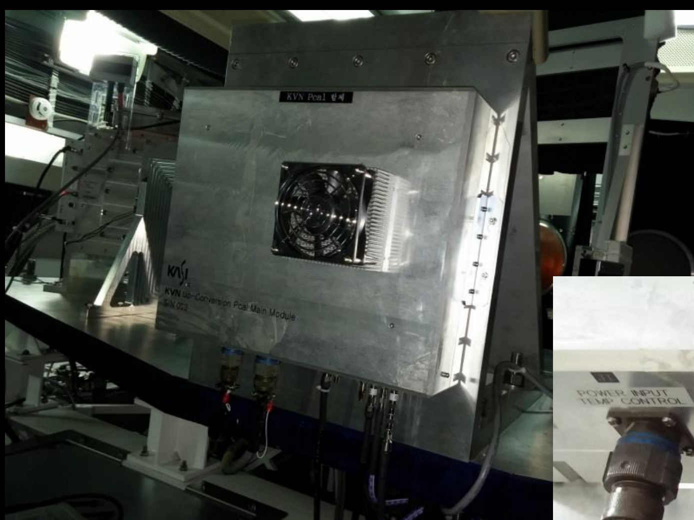
43, 129 GHz Receivers are omitted

Credit: D.H. Je

Pcal System Installed in Rx Room

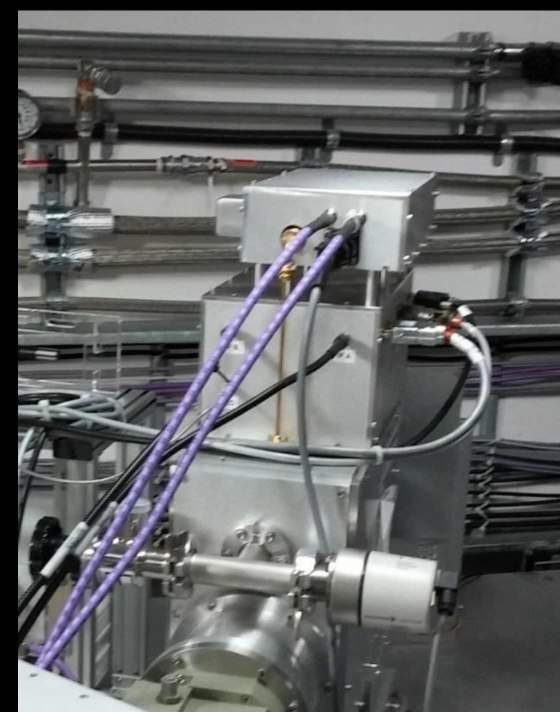
KYS

KUS

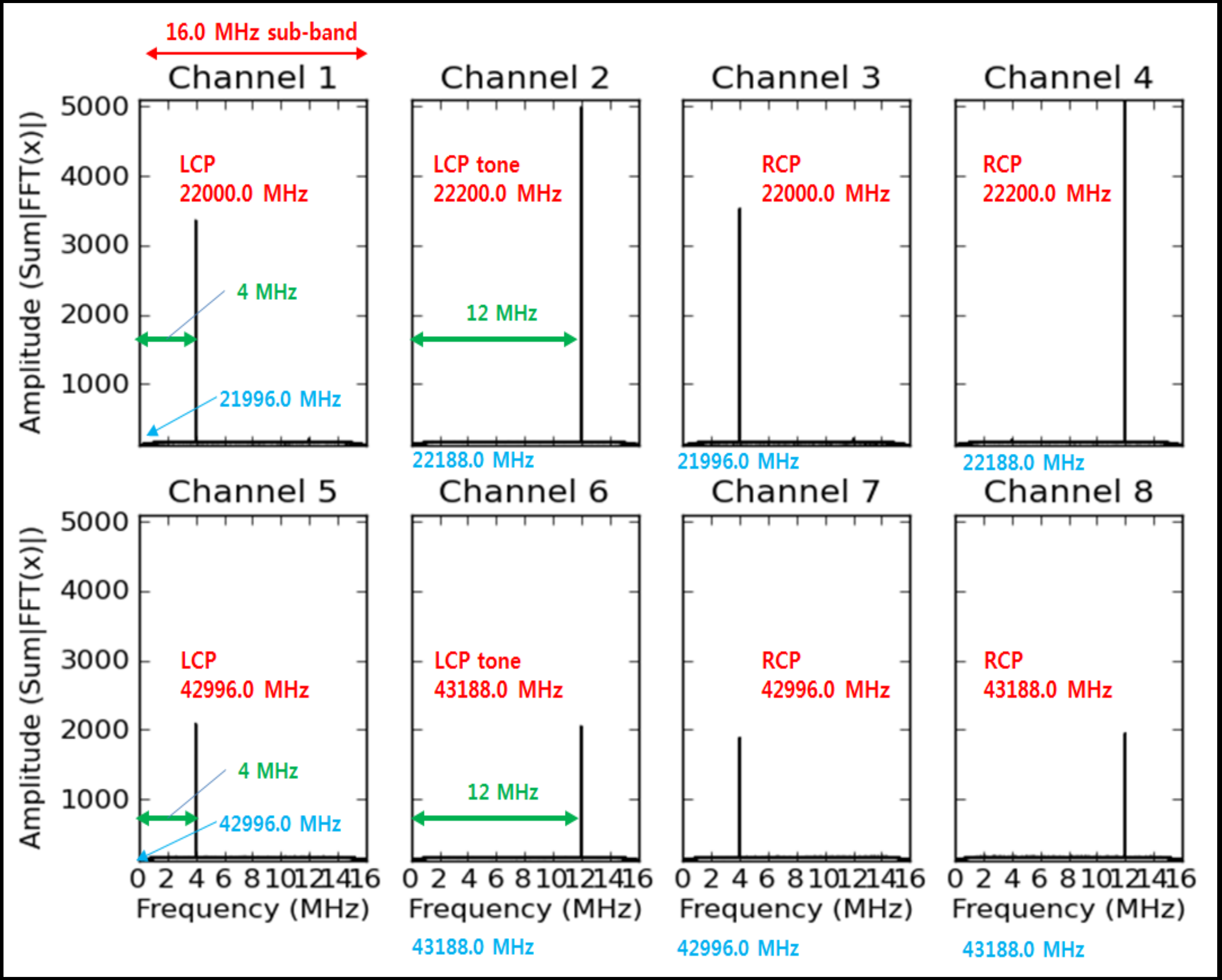


KTN

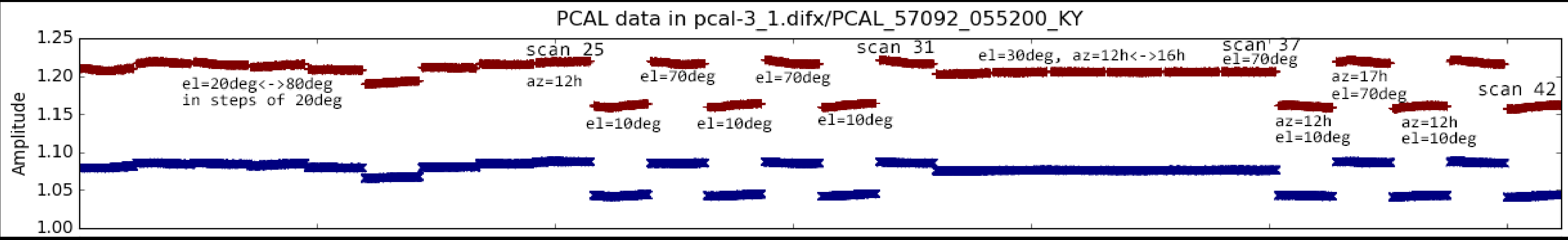
signal chain

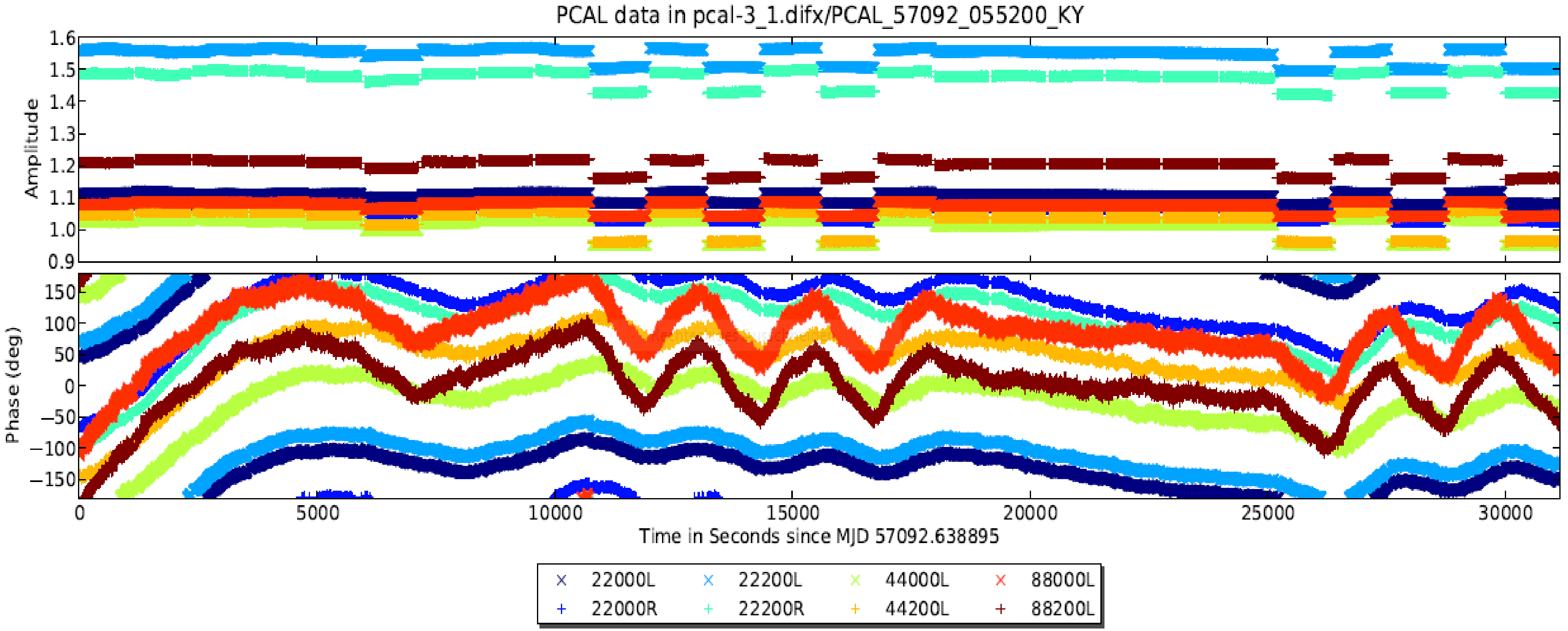


On-Site Pcal Test (KVN Yonsei Telescope)



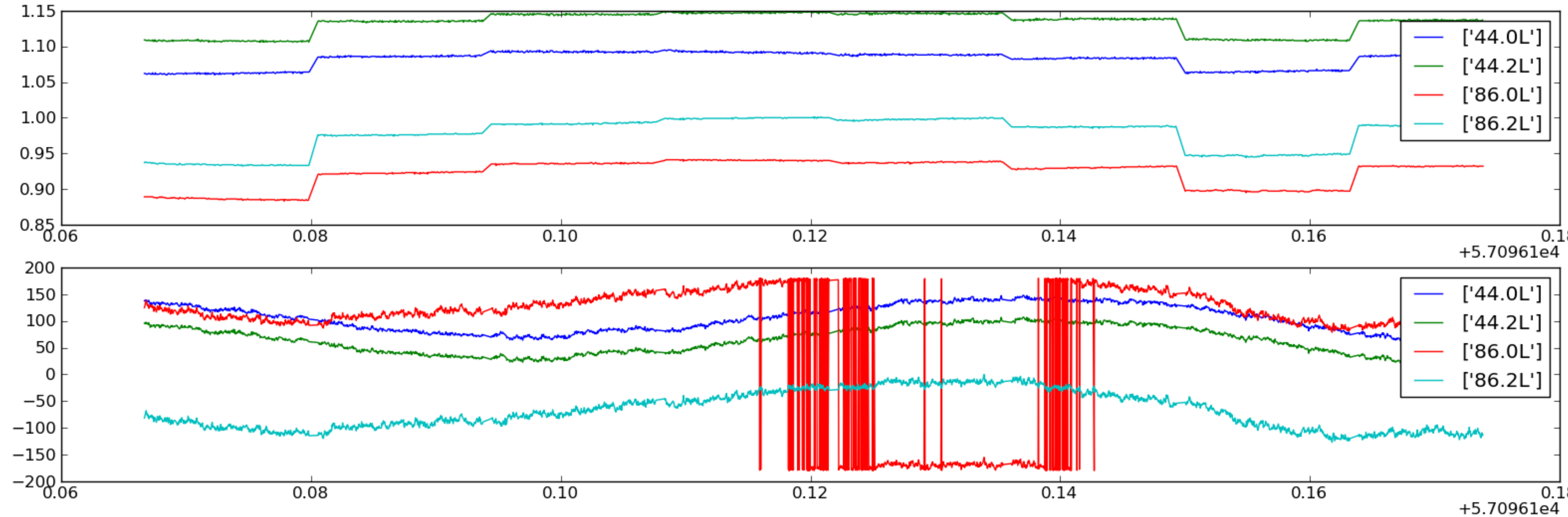
On Site Pcal Test (KVN Yonsei Telescope)

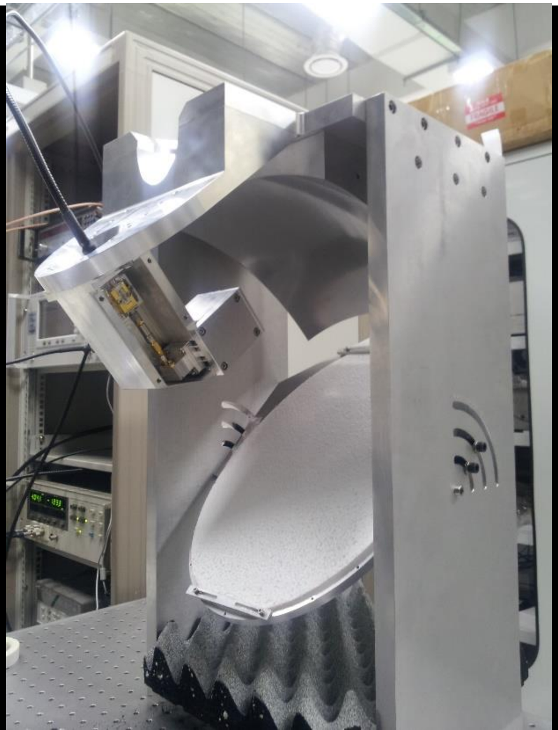




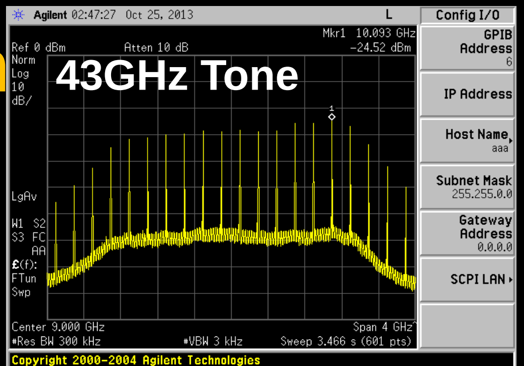
Jan Wagner (DiFX Pcal Extraction)

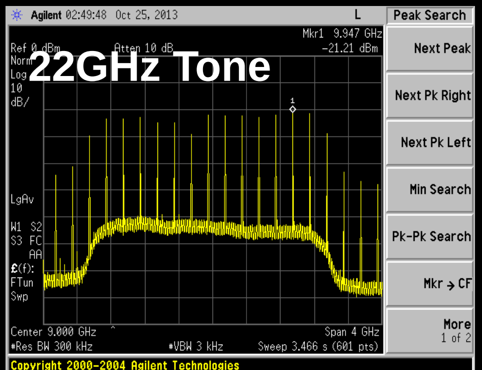
Quasi Optic Pcal Test

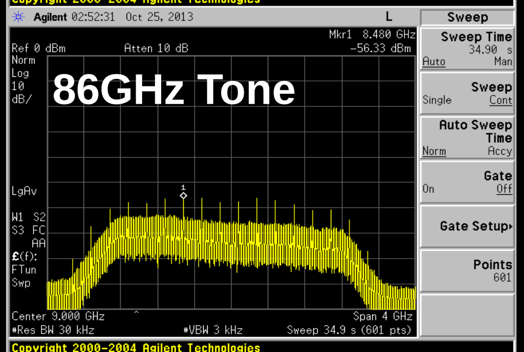




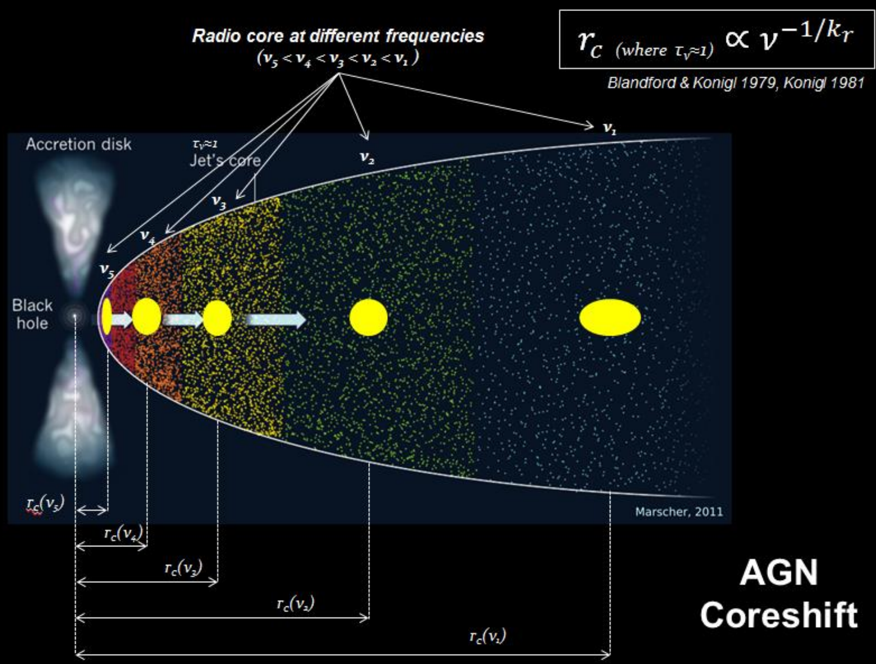
Quasi Optical Injection PCal System

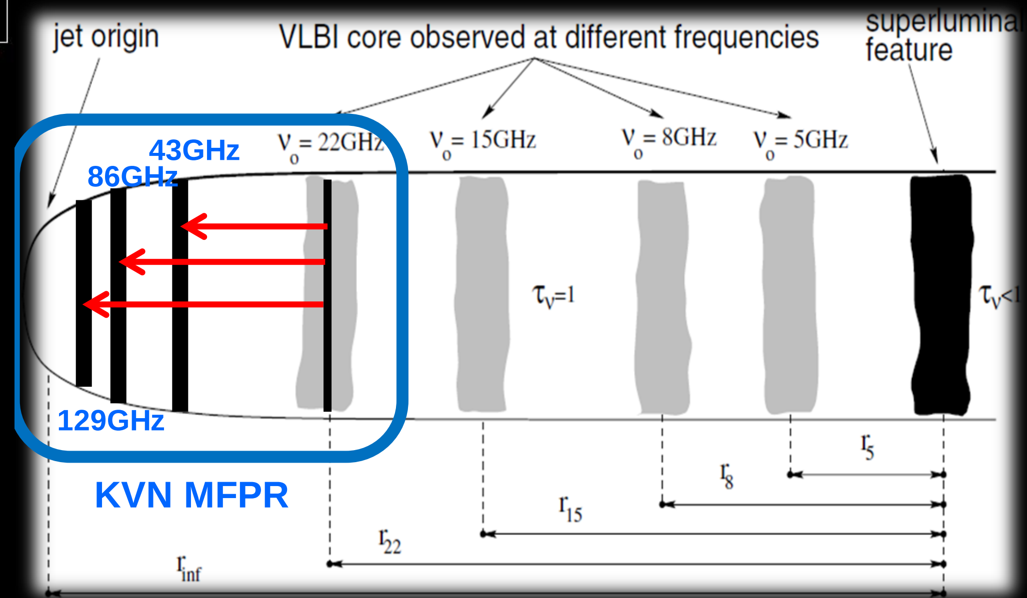


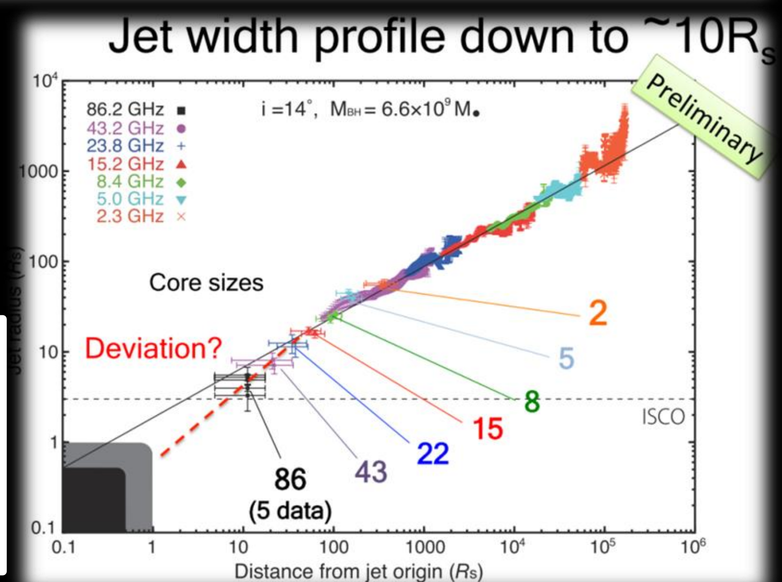




New Method in mm-VLBI Astrometry







Simultaneous multi-frequency observation

Perfect calibration to the troposphere

Ideal methods, especially mm/sub-mm VLBI

Unique access to the inner most region of the Jets
➔ High precision VLBI astrometry can be achieved at mm/sub-mm wavelengths with unprecedented sensitivity

Accurate Delay Errors Calibration

1. Large-scale systematic delay errors
≈ correlation model (apriori) errors
clock / instrumental errors

typically, $\Delta\tau_a > 5$ cm
→ this should be reduced ~ 1 cm level
→ method : GPS/JAM application (ion / troposhere)
EOP correction
Geodetic block or Multiple calibrators
Pcal & special observing design

2. (Relatively) small-scale (random) delay errors
≈ mostly weather related errors

typically, 0.05 cm (~15°) < $\Delta\tau_r$ < 0.5 cm (~150°) at 22GHz
→ nearby calibrators

GPS Installation - close collaboration with KASI GPS group

1. KVN antenna position

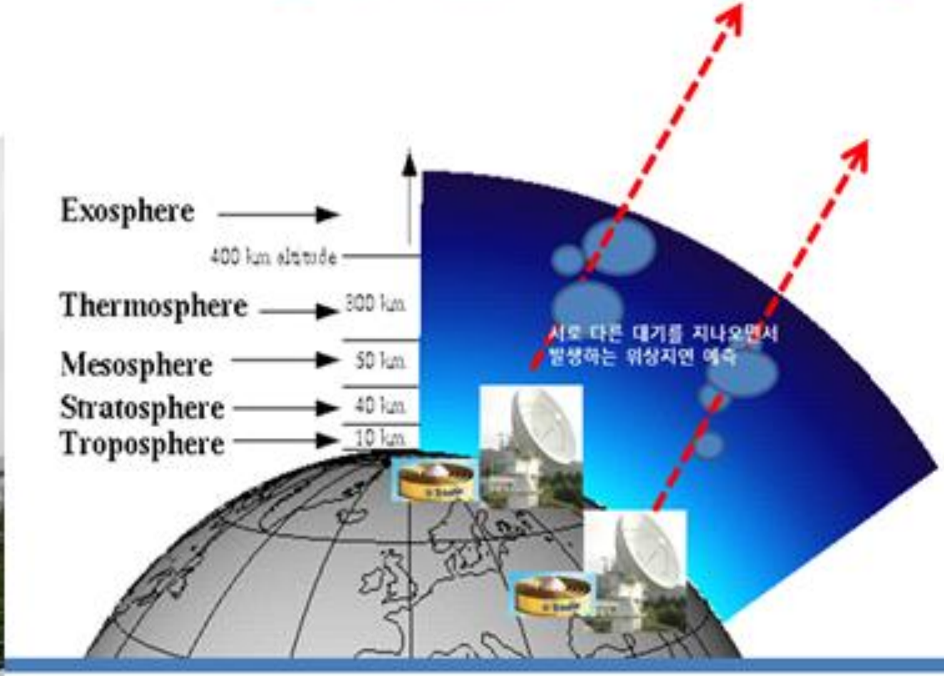
- displacement of KVN antenna position
- In-Variant Point (IVP) measurement

➔ To monitor accurate KVN antenna positions

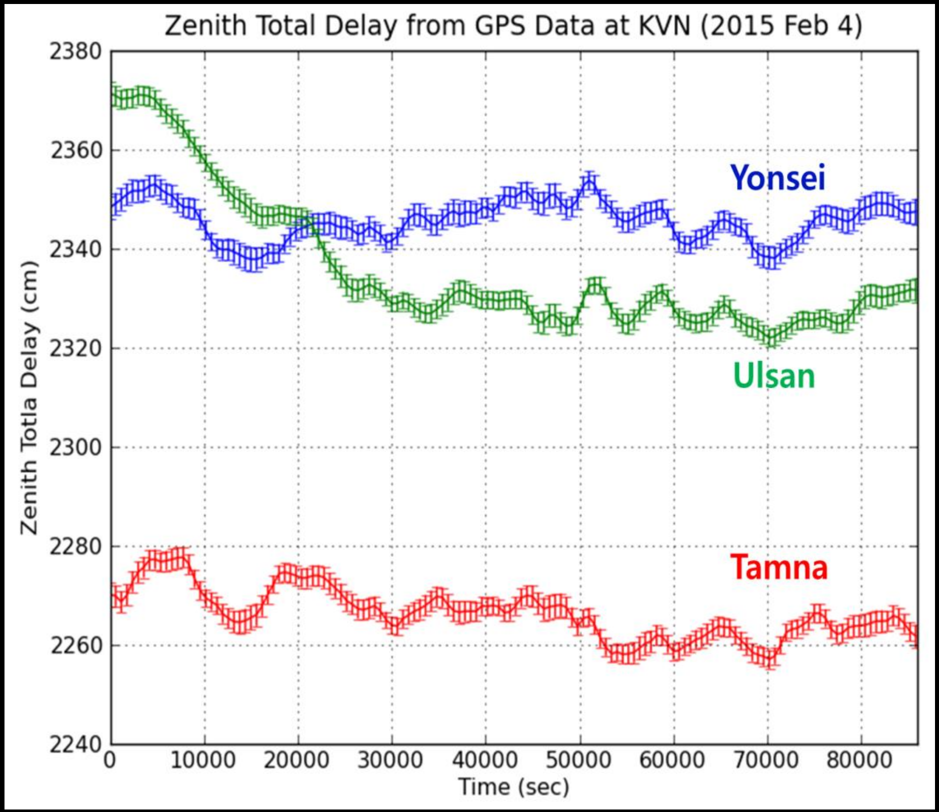
2. Atmospheric model calculation

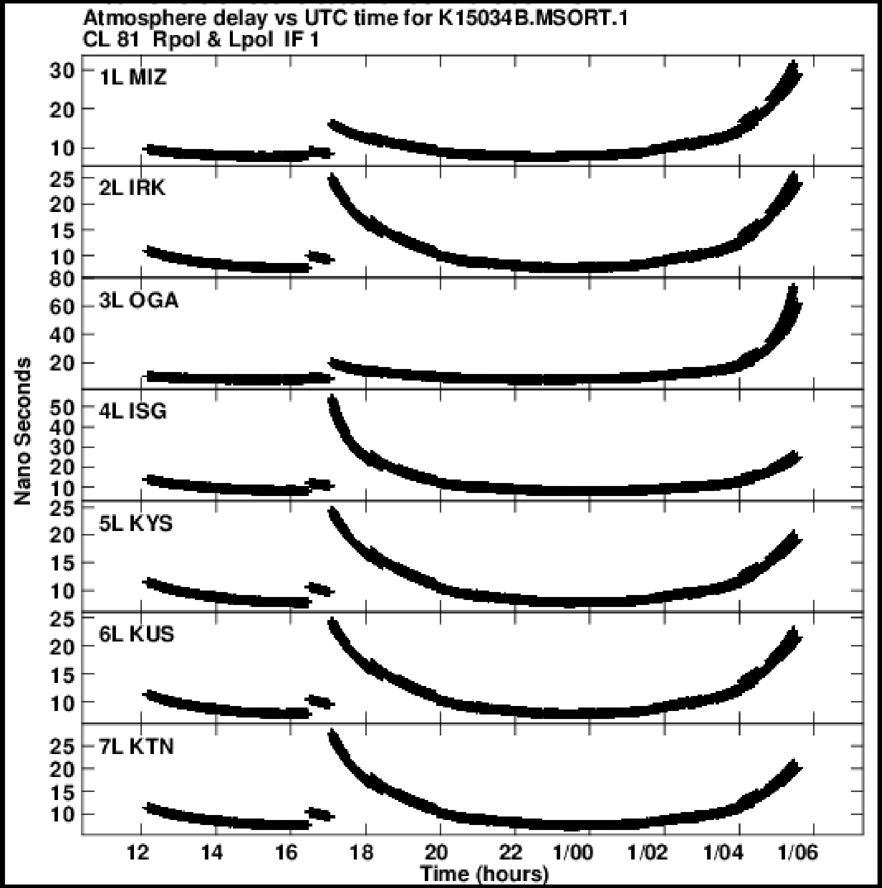
- Wet delay & TEC estimation

➔ To improve a phase referencing capability & astrometric accuracy



Delay Errors – GSP/JAM ZTD Inputs





ZTD (raw) from GPS
for KaVA 22GHz PR Test Observation

ZTD in AIPS from JAM
for KaVA 22GHz PR Test Observation

Intensive collaborations for the performance evaluation of KaVA PR is on-going on behalf of KaVA science WG


Thank you for your attention!
For the best mm-VLBI network
with Multi-frequency System
Tamna 21 m
Miyun 50 m
KASI/KJJVC
Sejong 22 m
Yonsei 21 m
Ulsan 21 m
Gifu 11 m
Usuda 64 m
Tomakomai 11 m
Nanshan 26 m
Mizusawa 20 m
Tianma 65 m
Takahagi 32 m
Sheshan 25 m
SHAO/DiFX
Kunming 40 m
Yamaguchi 32 m
Ishigakijima 20 m
Hitachi 32 m
Iriki 20 m
Tsukuba 32 m
Ogasawara 20 m
Kashima 34 m
The East-Asian VLBI Network
(Image Credit: Reto Stöckli, NASA Earth Observatory)
6.7 GHz
8 GHz
22 GHz
43 GHz