Multi-Frequency VLBI Telescopes & Synergy with ALMA

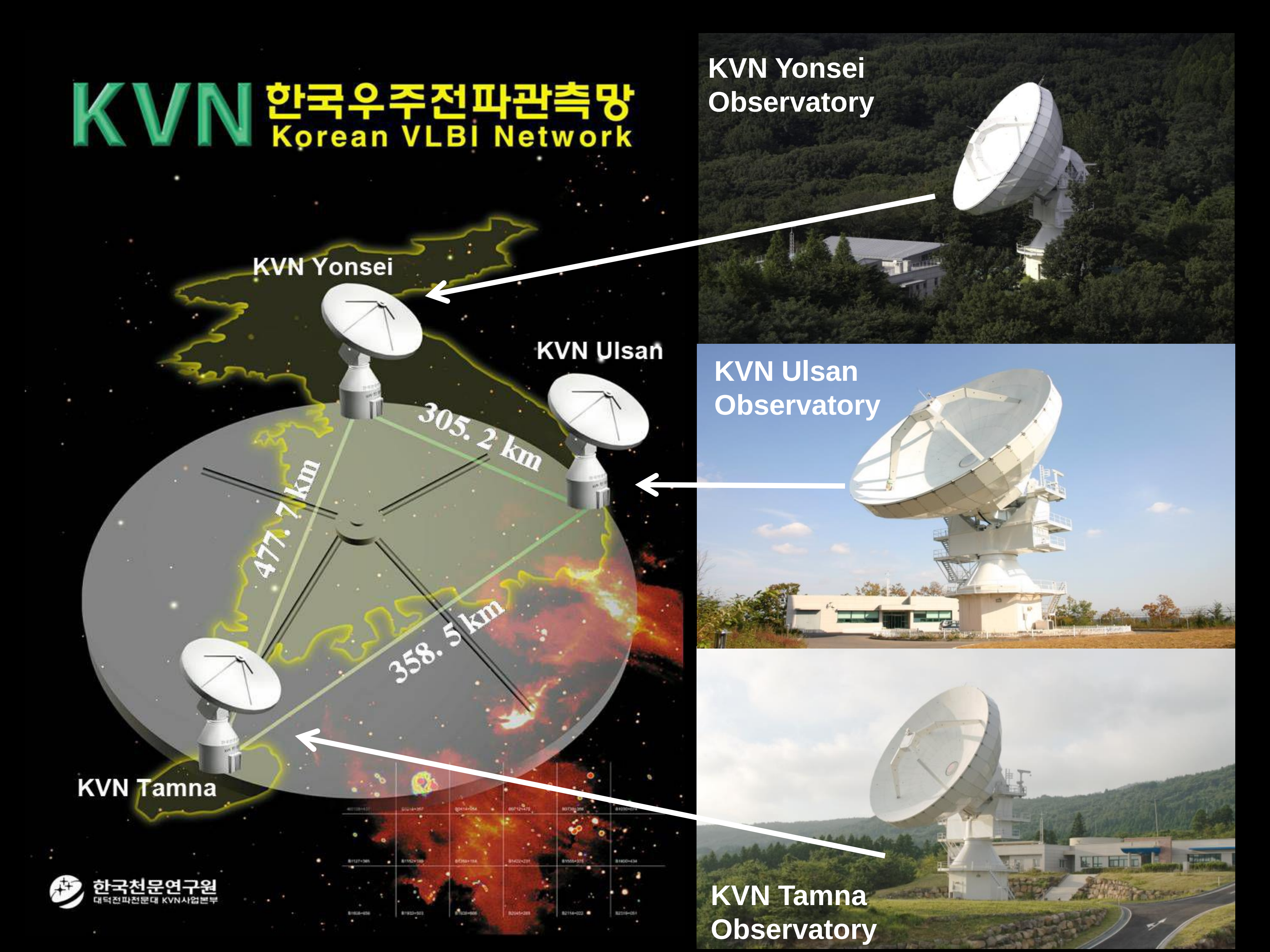
Taehyun Jung

Korean VLBI Network (KVN)
Korea Astronomy & Space Science Institute (KASI)

Workshop on mm-VLBI with ALMA @ Istituto di Radioastronomia Bologna, Italy Jan. 22–23, 2015

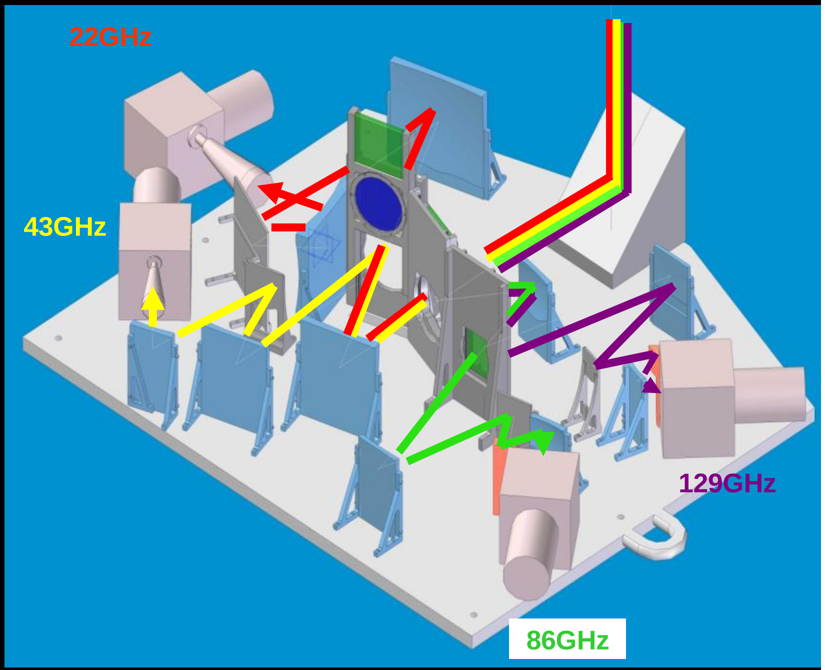
Korean VLBI Network

Multi-frequency mm-VLBI system

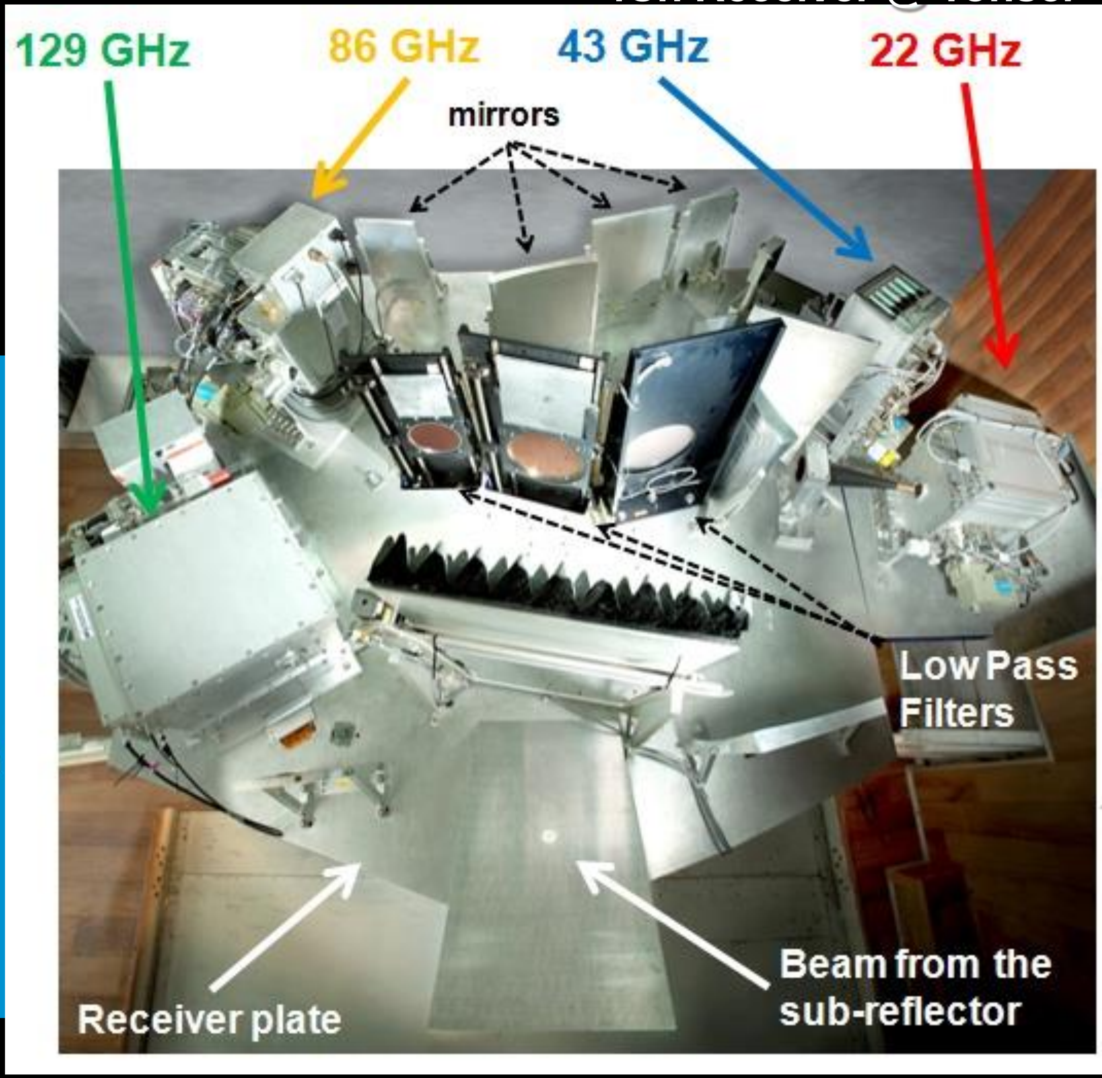

KVN 한국우주전파관측망
Korean VLBI Network
KVN Yonsei
KVN Ulsan
KVN Tamna
305. 2 km
477. 7 km
358. 5 km
한국천문연구원
대덕전파천문대 KVN사업본부
KVN Yonsei Observatory
KVN Ulsan Observatory
KVN Tamna Observatory

Multi-Frequency Receiving System

Beams from antenna



4Ch Receiver @ Yonsei

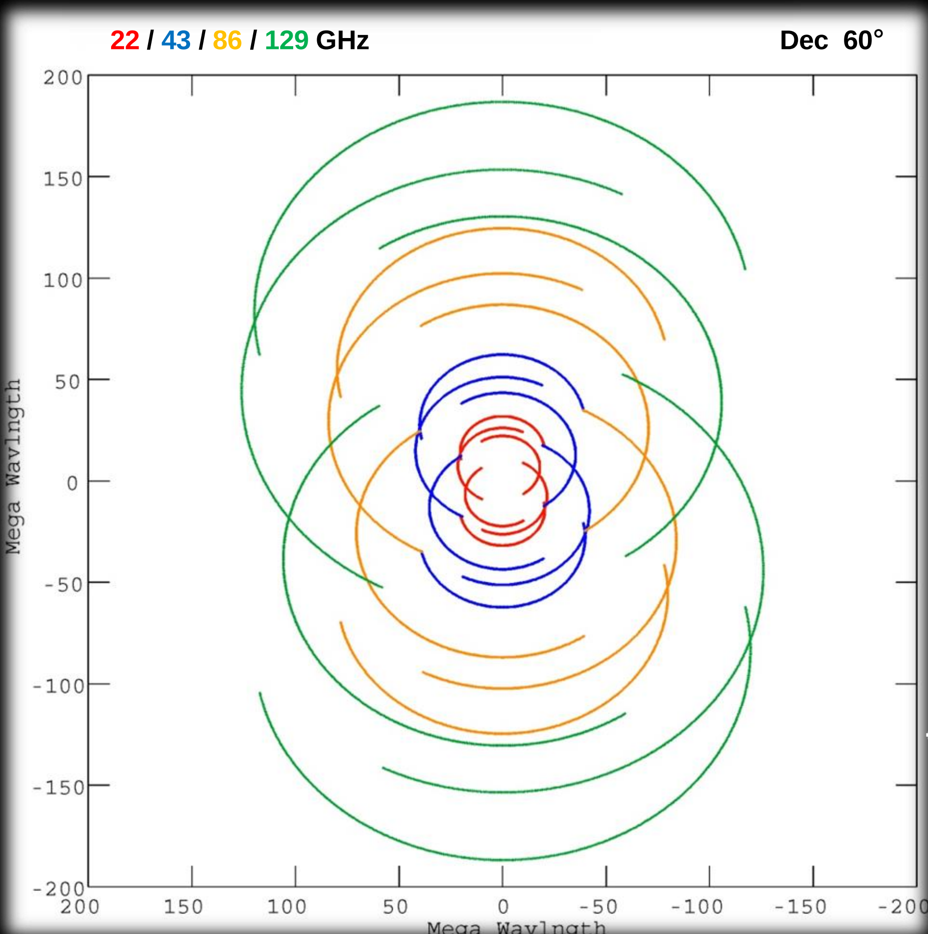


Band	K	Q	W	D
Freq. Range	21.25-23.25	42.11-44.11	85-95	125-142
Trx (K)	30-40	70-80 (40-50 KUS)	80-100	50-80

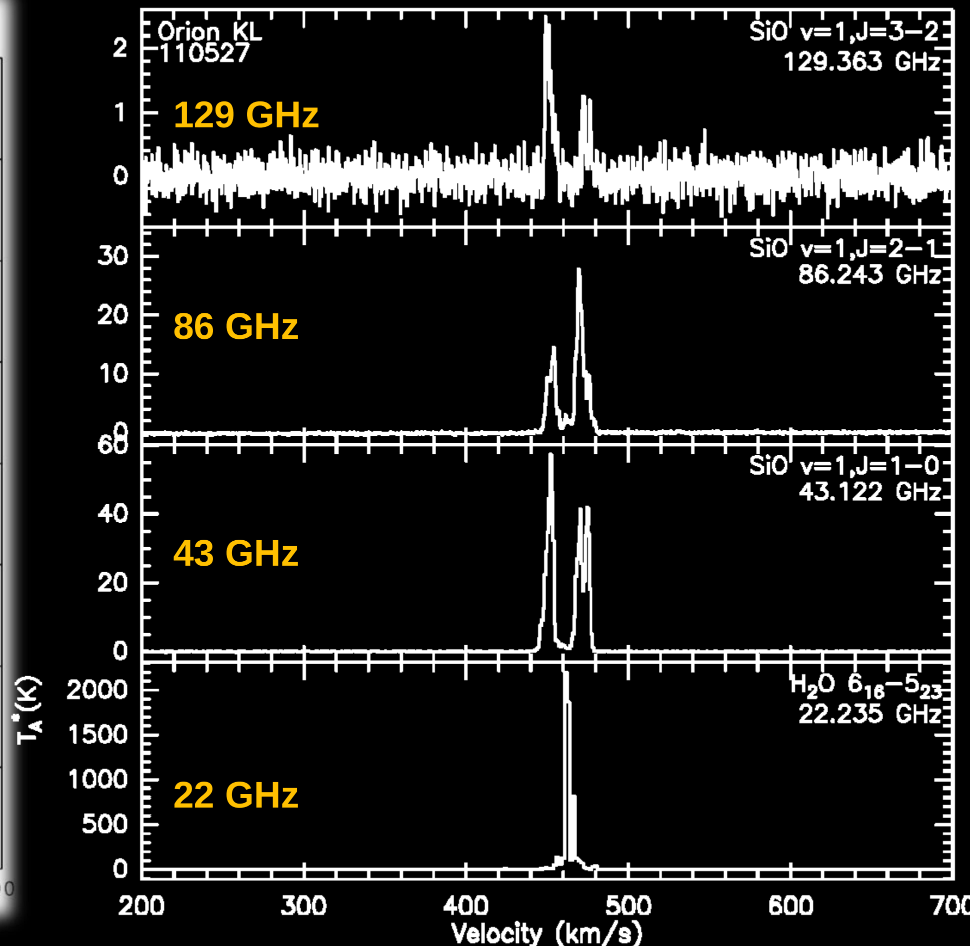
Full Polarization

Han et al. (2008)

First Light from 22/43/86/129 GHz Simultaneous Single Dish Observation

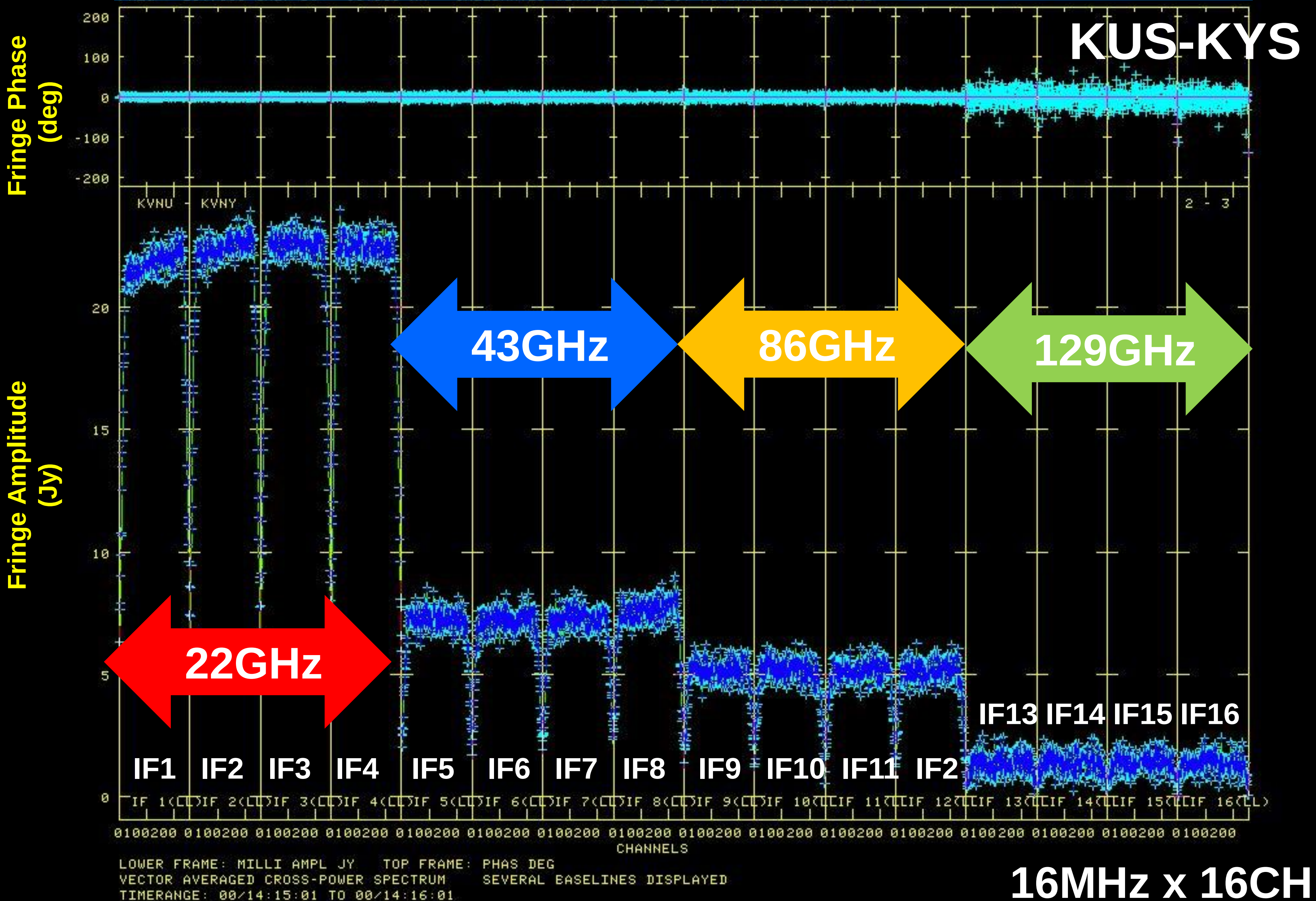


4CH UV Coverage



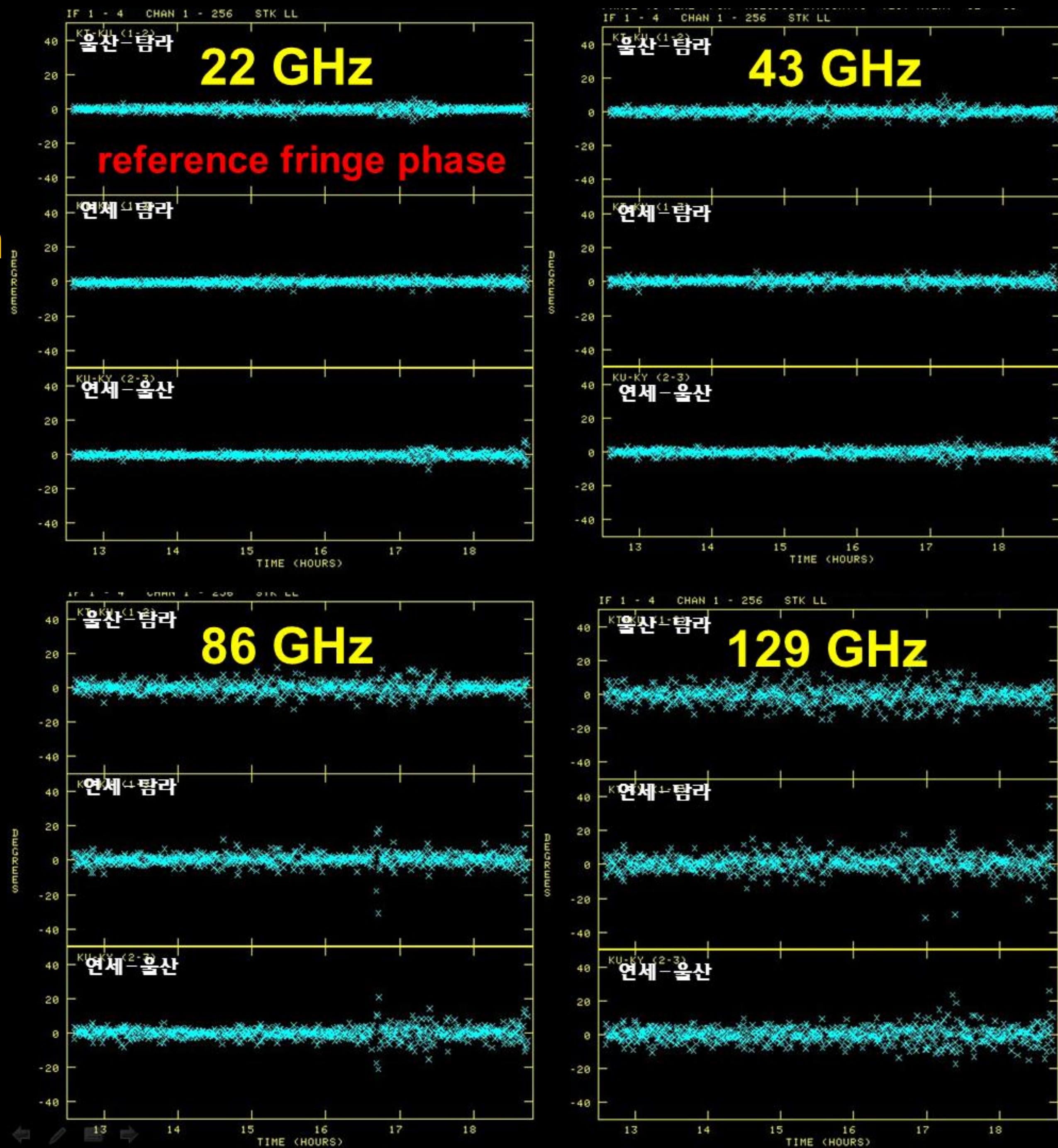
H20/SiO Masers in Orion KL

1st KVN VLBI 4-band Fringes (2012 April)



KVN 4-Channel Simultaneous VLBI Observation

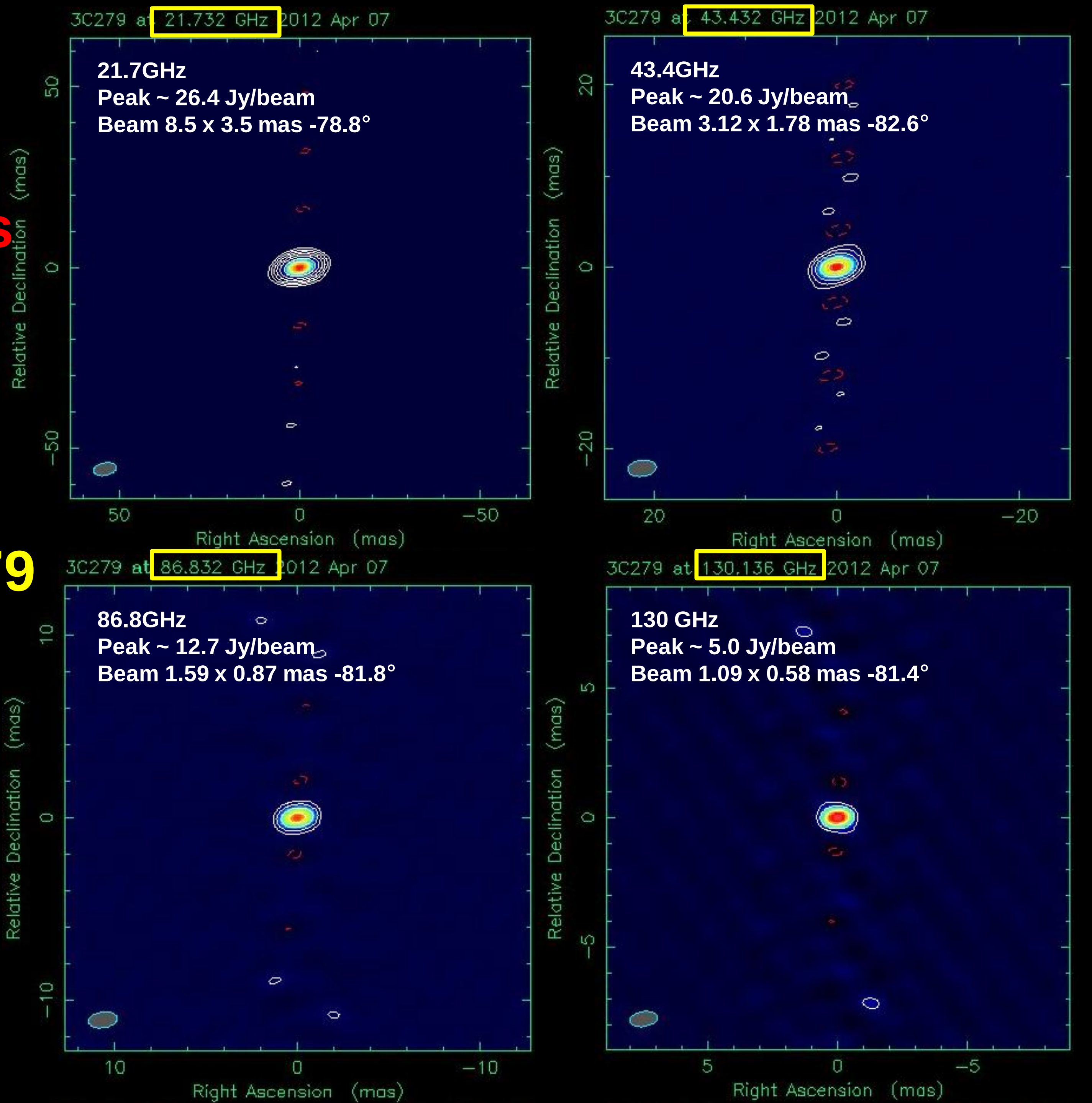
MFRP applied
source: 3C279



Obscode: k12098c

First KVN's 4-channel Simultaneous Observation VLBI Images

Source: 3C279



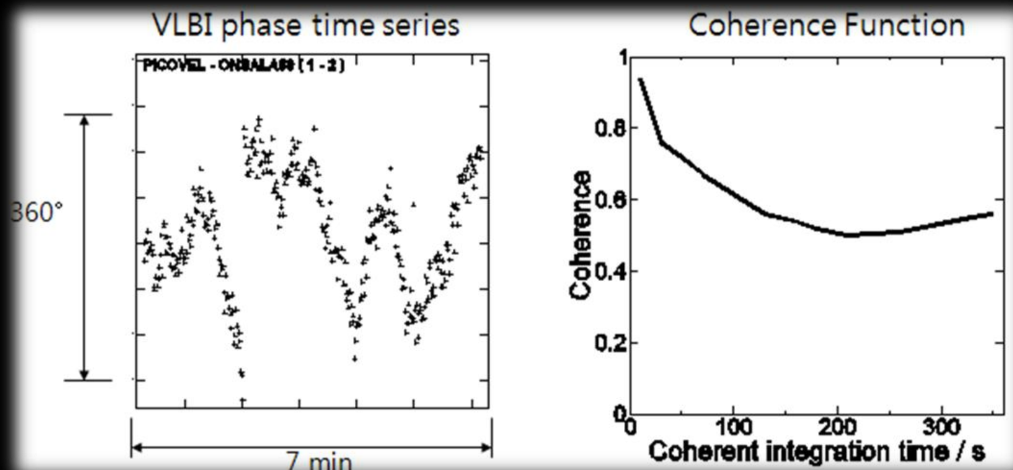
43/86/130GHz visibility phases are calibrated by 22Ghz

Difficulties in mm/sub-mm VLBI

Phase Referencing Techniques

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

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

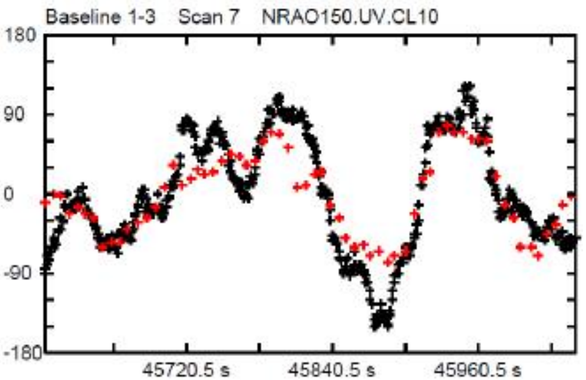
Pico Veleta – Onsala baseline (A. Roy)
Source : BL Lac
Frequency : 86 GHz

Coherence Time

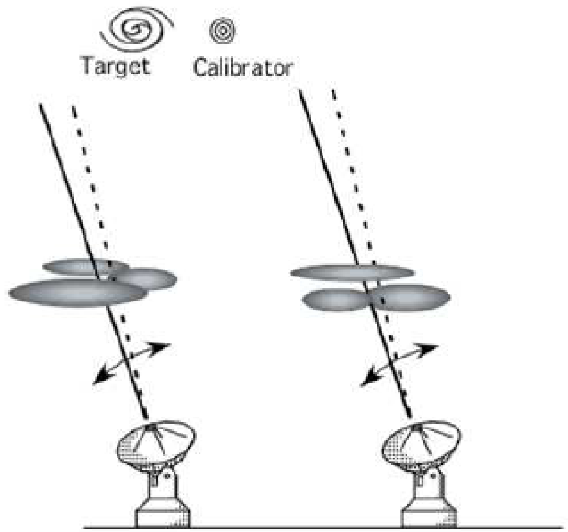
Frequency (GHz)	2	8	15	22	43	86	129
Coherence Time (sec)*	800	200	100	73	37	19	12

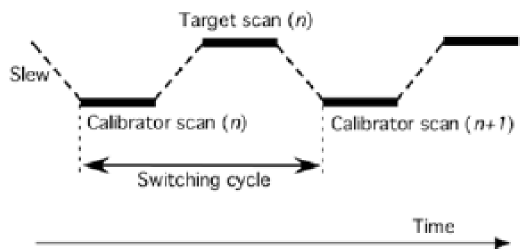
*Typical value of atmospheric phase stability ~ 10^{-13}

Phase Referencing Techniques

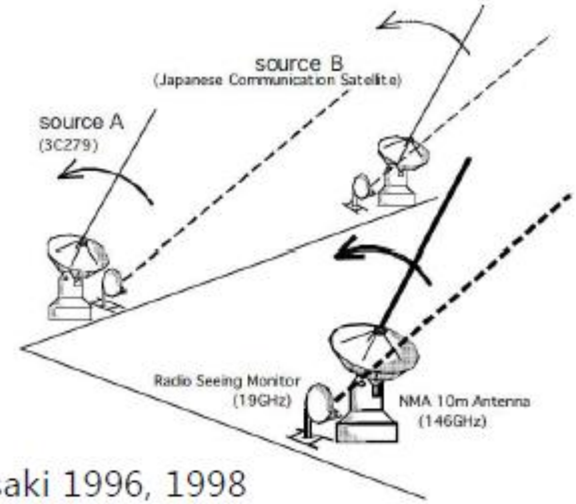


VLBI phase time series (black) and
WVR-derived phase correction (red)
(Roy et al. 2006)

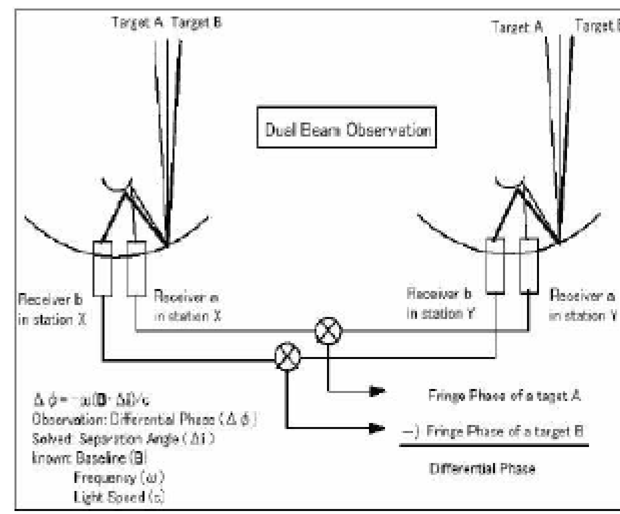




(source : Asaki)



Asaki 1996, 1998



Phase Referencing Methods

PR Methods	Reference SRC problem	Obs.Time loss	Coherence loss	etc
Water Vapor Radiometry	No	No	No	Water droplet problem Relatively lower cost
Fast Antenna Switching	Yes	Yes	Yes	General PR methods Lower cost
Paired/Clustered Antenna	Yes	No	Yes	Connected arrays Higher cost
Dual-Beam Antenna	Yes	No	No	Astrometry
Fast Frequency Switching	Yes	Yes	Yes	Weak source imaging
Bigradient Phase Referencing	Some	Yes	Yes	Weak source imaging
SFPR With Freq. Switching	No	Yes	Yes	Weak source imaging Astrometry
SFPR with Multi-Frequency System	No	No	No	Weak source imaging Astrometry

Phase Referencing Methods

PR Methods	Reference SRC problem	Obs.Time loss	Coherence loss	etc
Water Vapor Radiometry	No	No	No	Water droplet problem Relatively lower cost
Fast Antenna Switching	Yes	Yes	Yes	General PR methods Lower cost
Paired/Clustered Antenna	Yes	No	Yes	Connected arrays Higher cost
Dual-Beam Antenna	Yes	No	No	Astrometry
Fast Frequency Switching	Yes	Yes	Yes	Weak source imaging
Bigradient Phase Referencing	Some	Yes	Yes	Weak source imaging
SFPR With Freq. Switching	No	Yes	Yes	Weak source imaging Astrometry
SFPR with Multi-Frequency System	No	No	No	Weak source imaging Astrometry

Multi-Frequency Phase Referencing (MFPR)

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

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

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

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

Source Structure

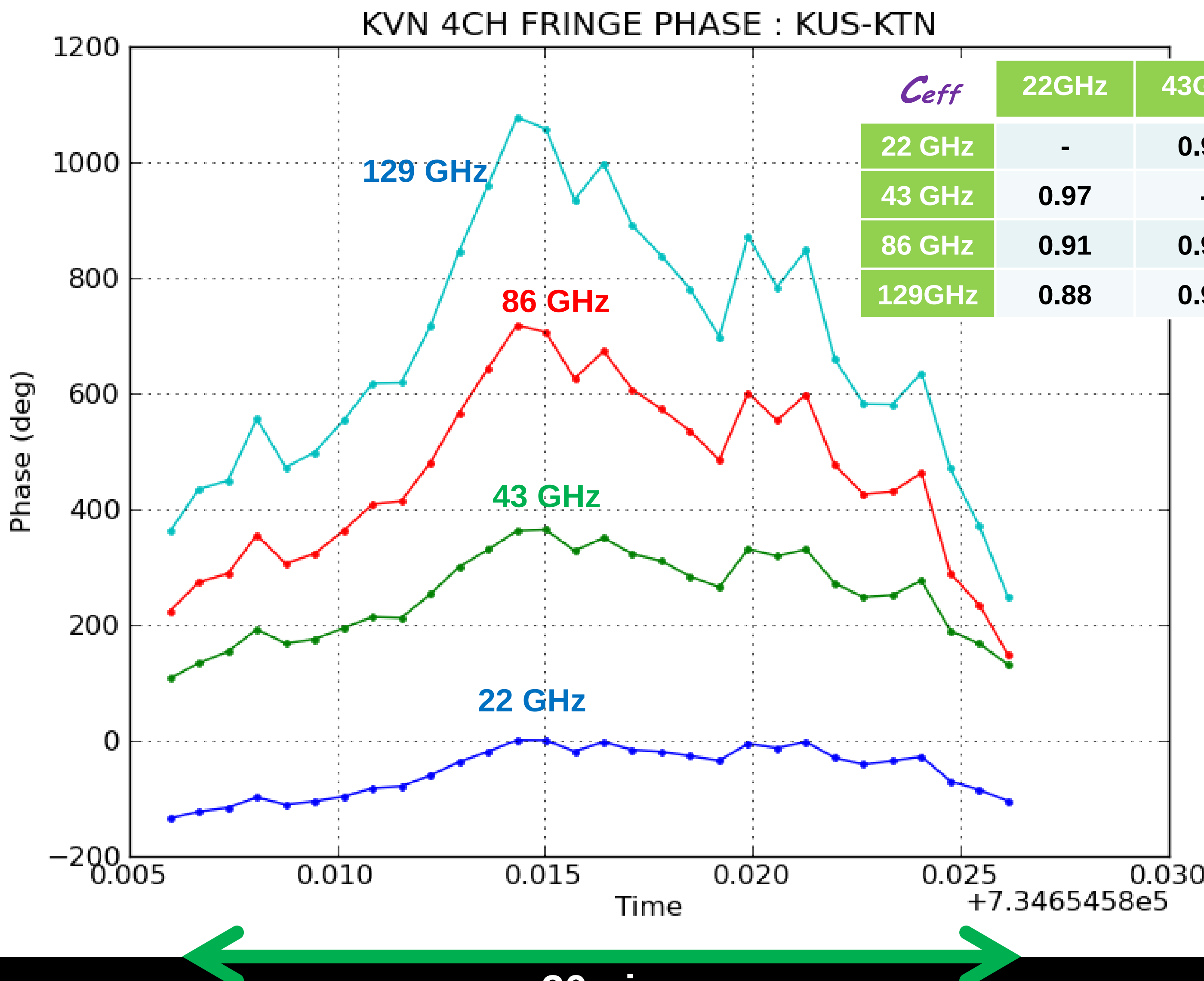
Core-shift
diff in maser lines

ionosphere

instrument

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

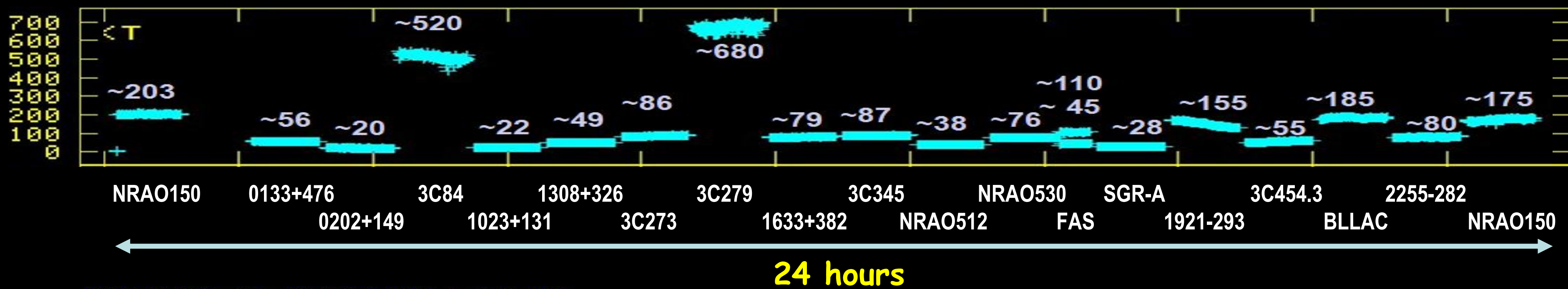
MFPR KVN 4CH Simultaneous Observation

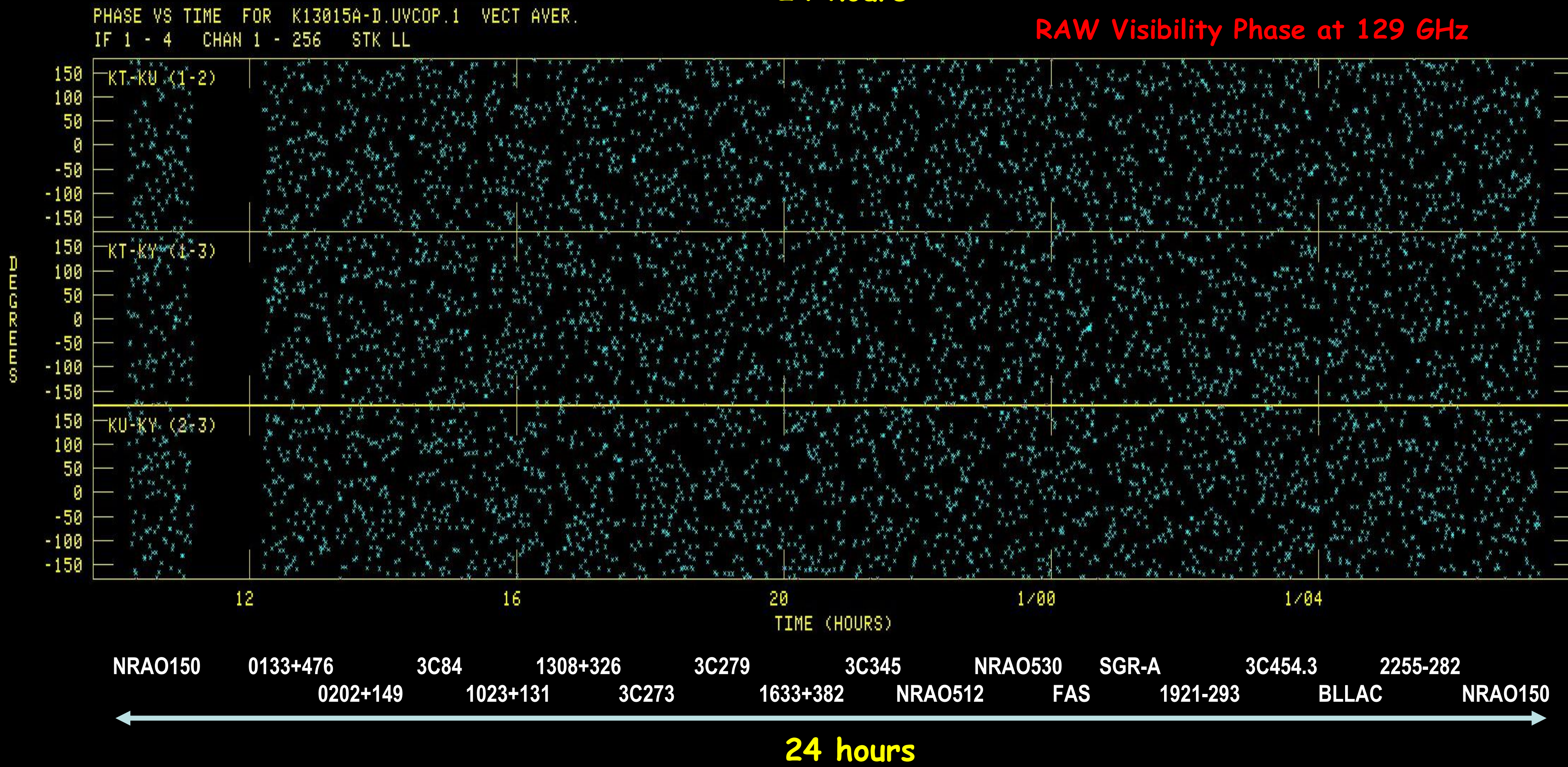


C_{eff}	22GHz	43GHz	86GHz	129GHz
22 GHz	-	0.97	0.91	0.88
43 GHz	0.97	-	0.97	0.96
86 GHz	0.91	0.97	-	0.99
129GHz	0.88	0.96	0.99	-

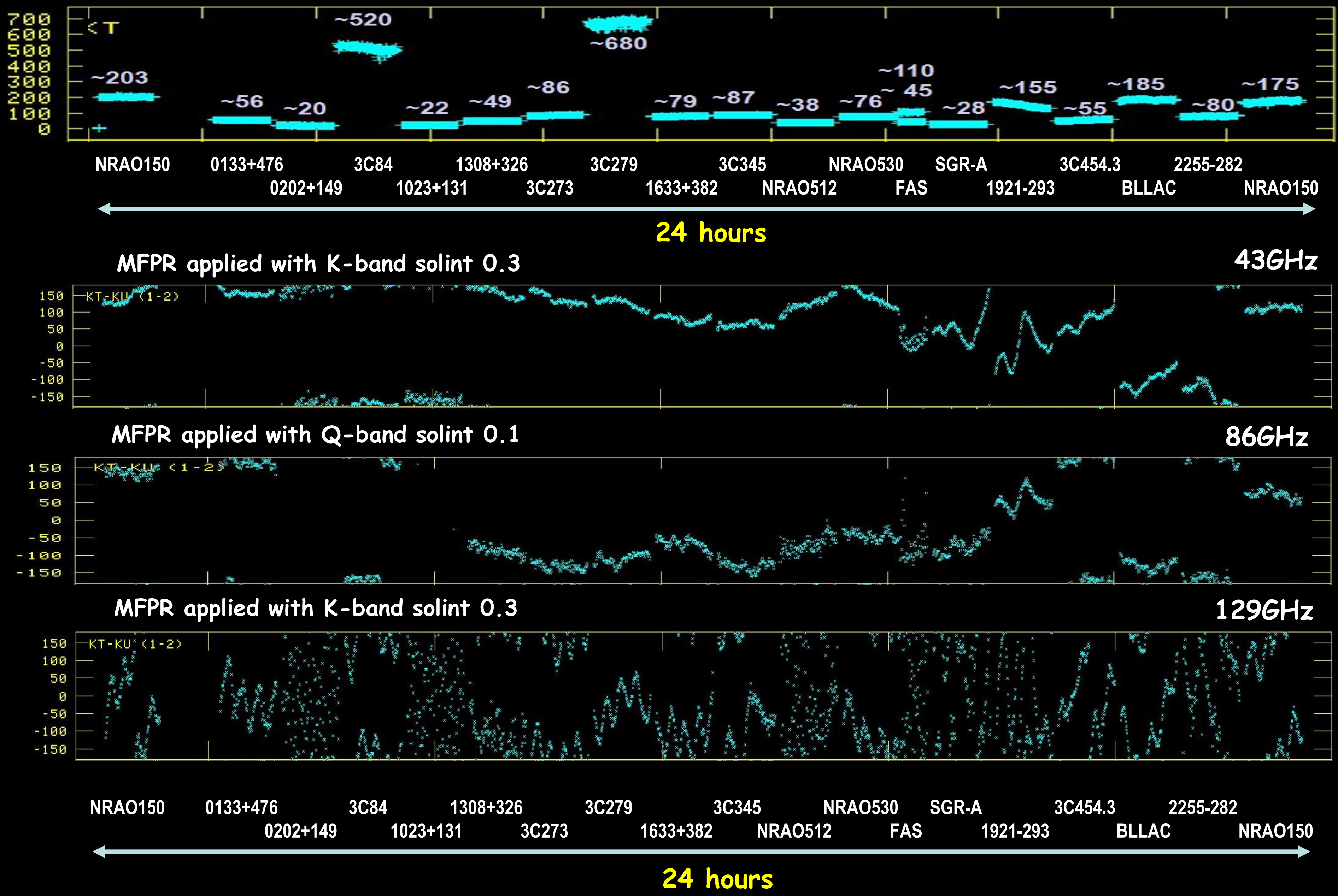
30min

High frequency Phase Calibration by Lower Frequency

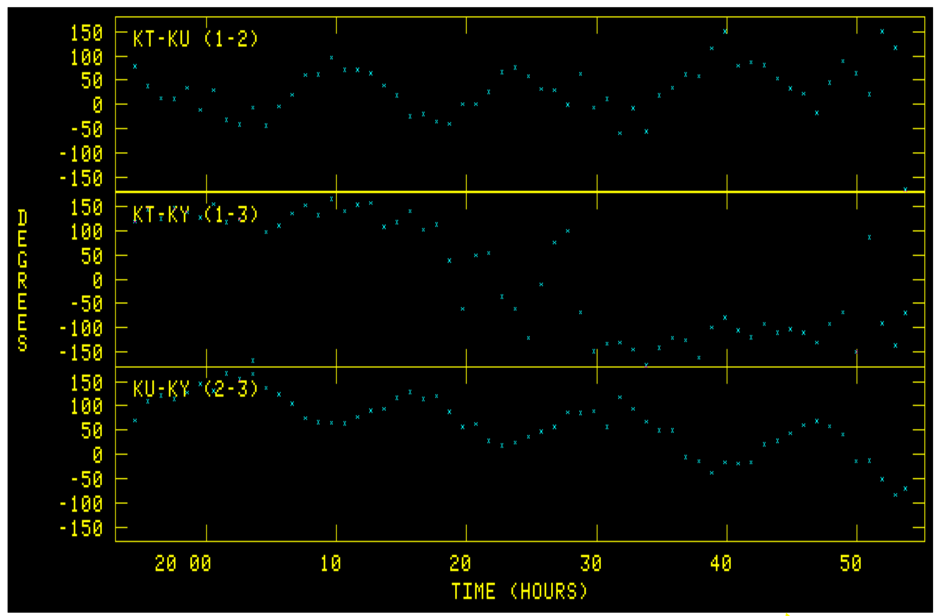


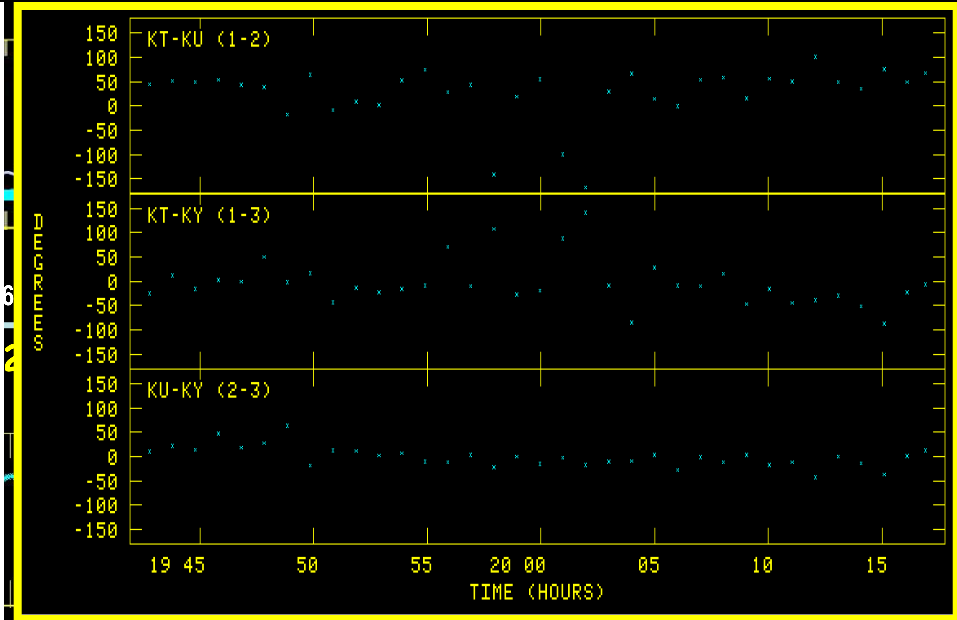


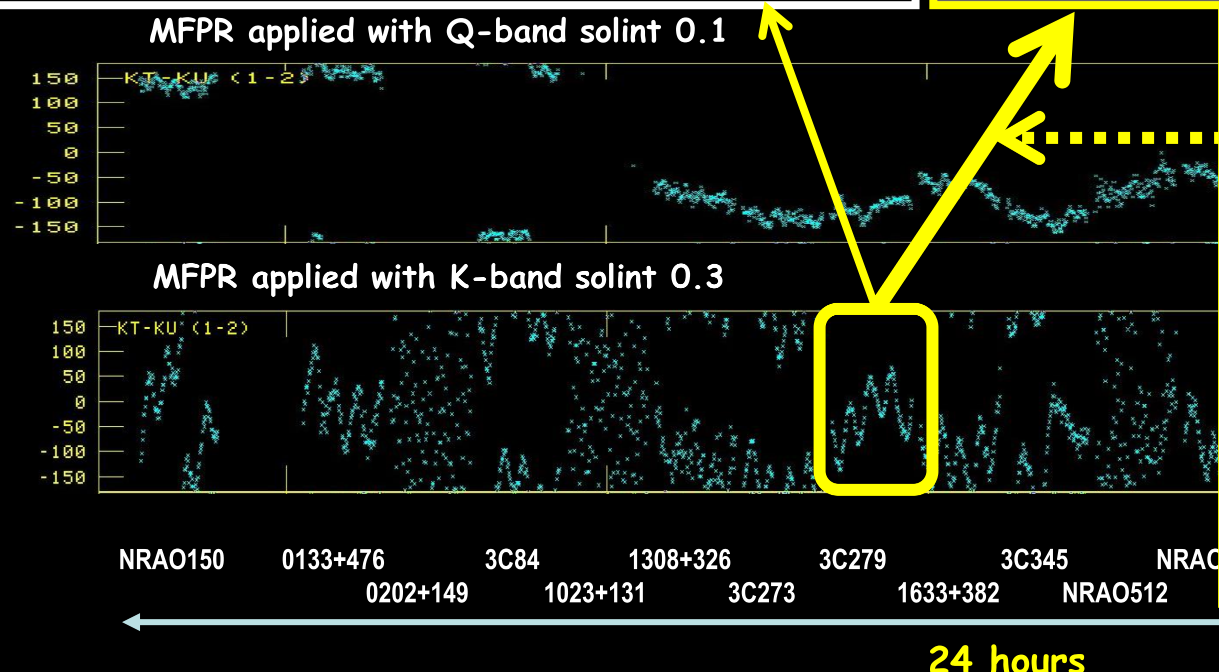
High frequency Phase Calibration by Lower Frequency



43GHz & 86GHz Visibility Phase referenced by 22GHz





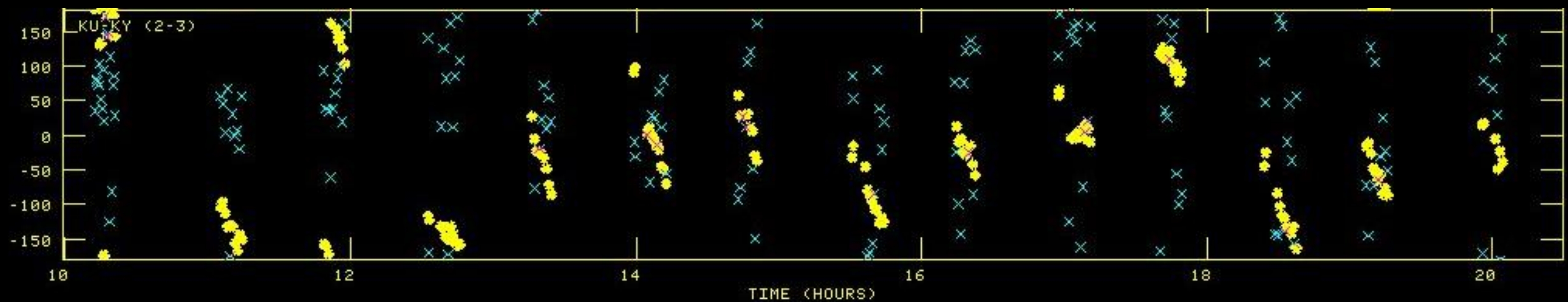


New thermal control system at KVN Yonsei Rx Room

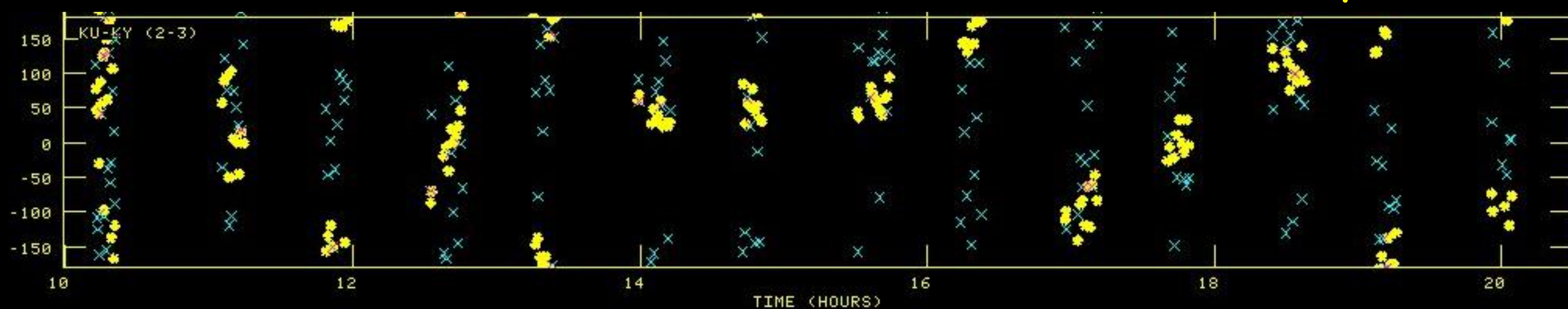
Comparison: Raw Visibility Phase & FPT Phase for M87

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

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

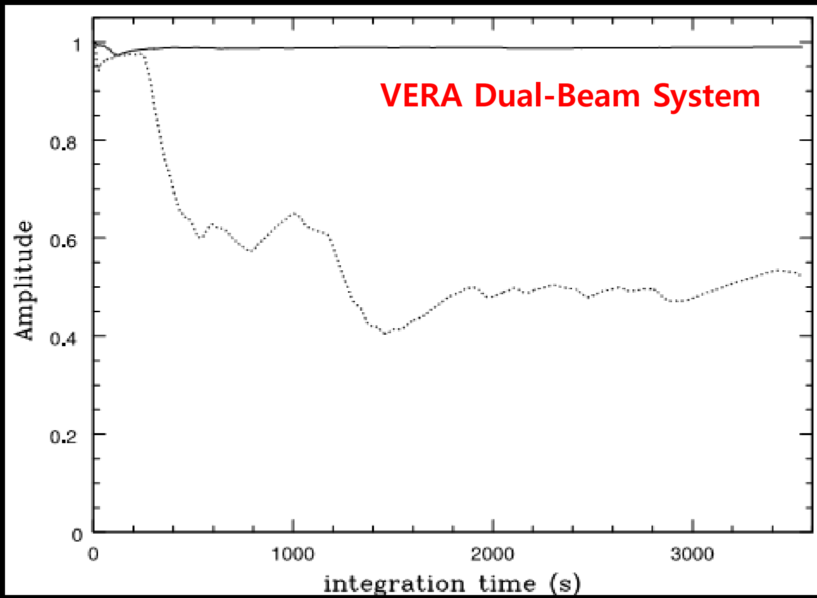


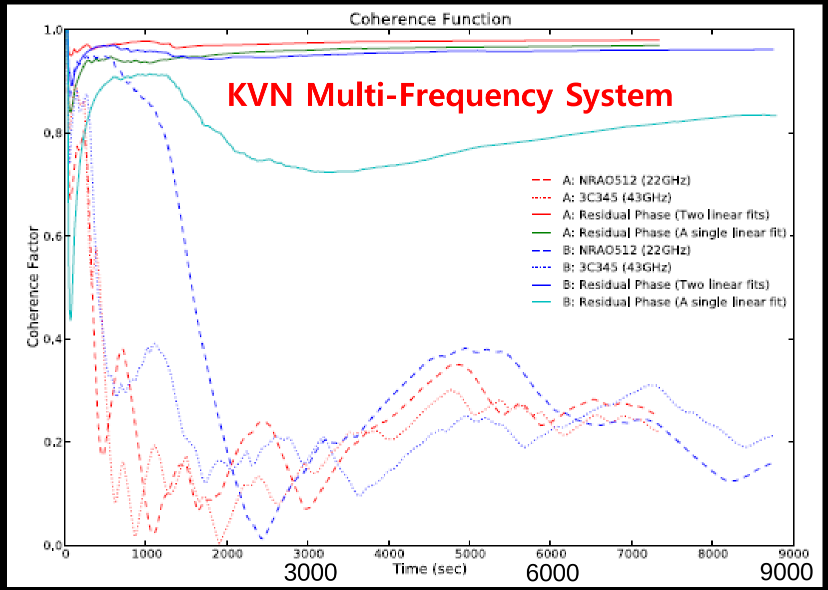
129GHz Raw & FPT (22GHz phase x 6)



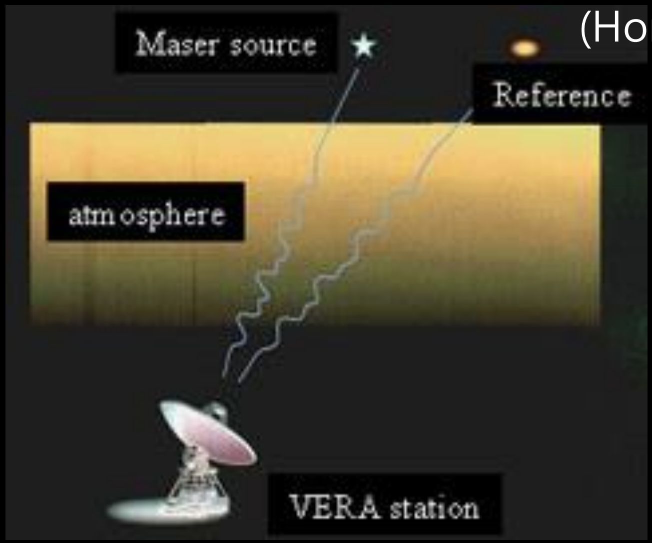
Two Main Reasons in VLBI Phase Referencing

1. Increase coherence time → weak source detection with high SNR

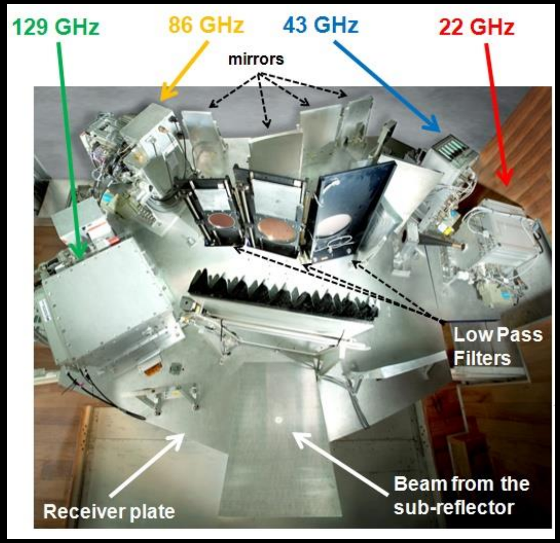




(Honma+2003)

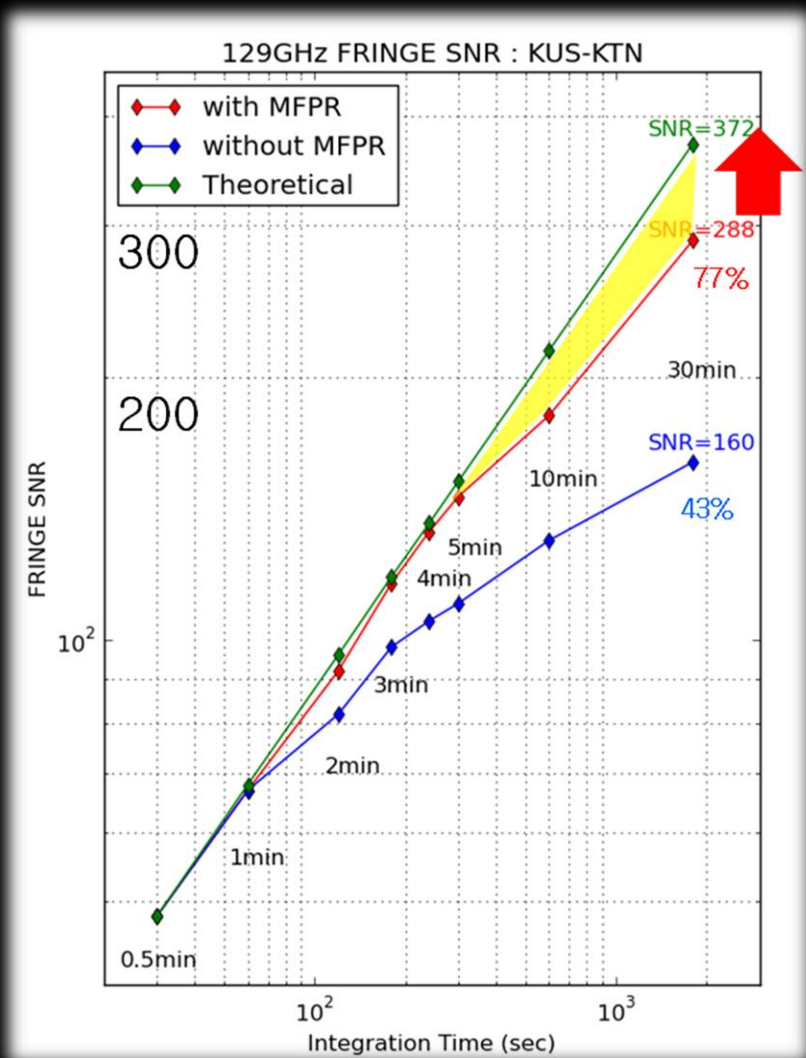


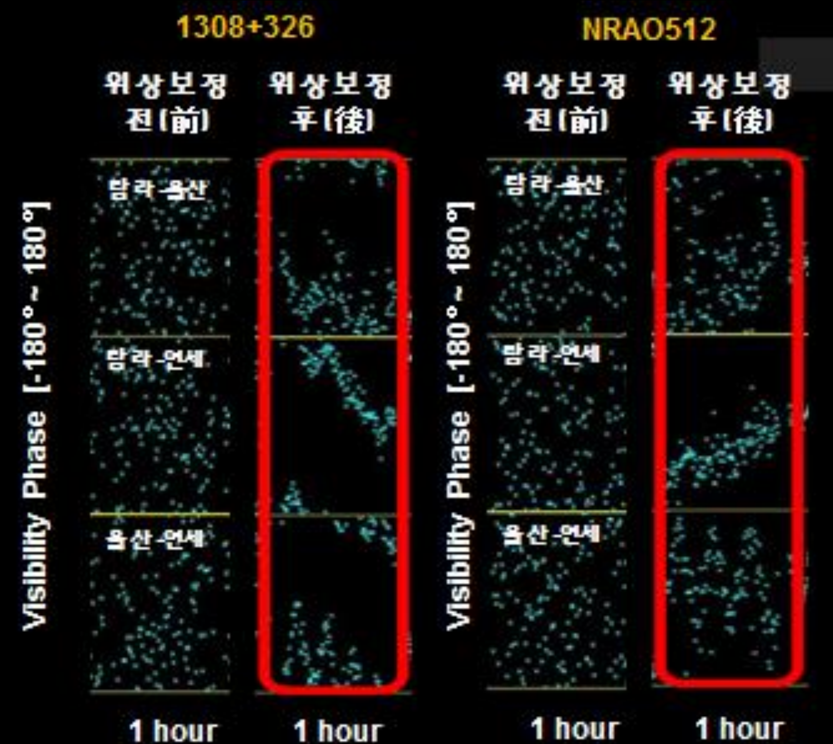
(Jung+2011)



Two Main Reasons in VLBI Phase Referencing

1. Increase coherence time → weak source detection with high SNR



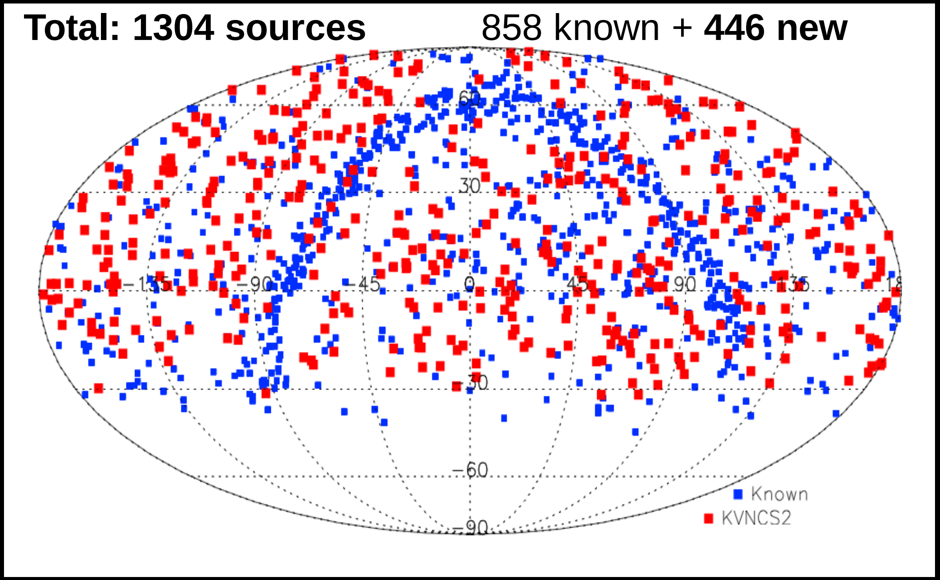


The First VLBI Detection of 1308+326 & NRAO512 at 129 GHz

Source	1308+326	NRAO512
SNR	130	100
Flux (mJy/beam)	300~420	160~250

Multifrequency AGN Survey with the KVN

Discovering high-frequency sources & Maximizing the KVN uniqueness



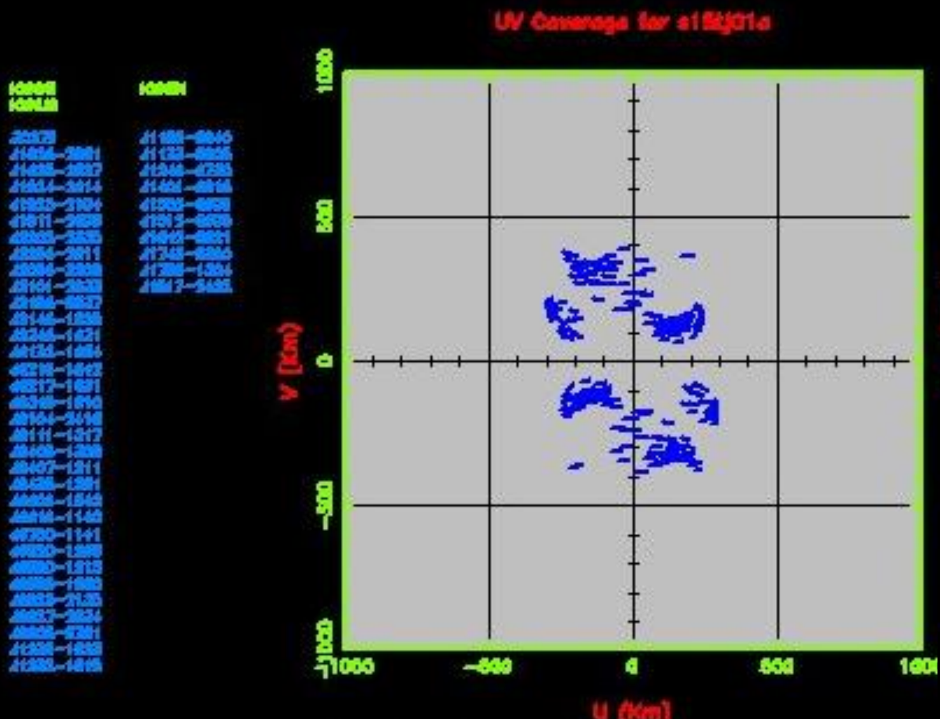
KVN Calibrator Survey (22/43GHz) by J.A. Lee

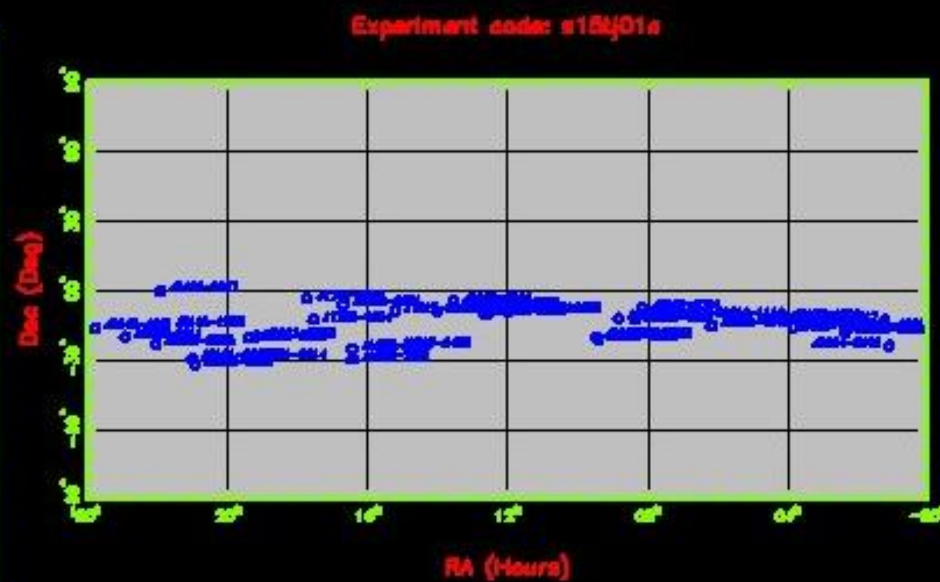
Multi-frequency source catalogue of selected samples

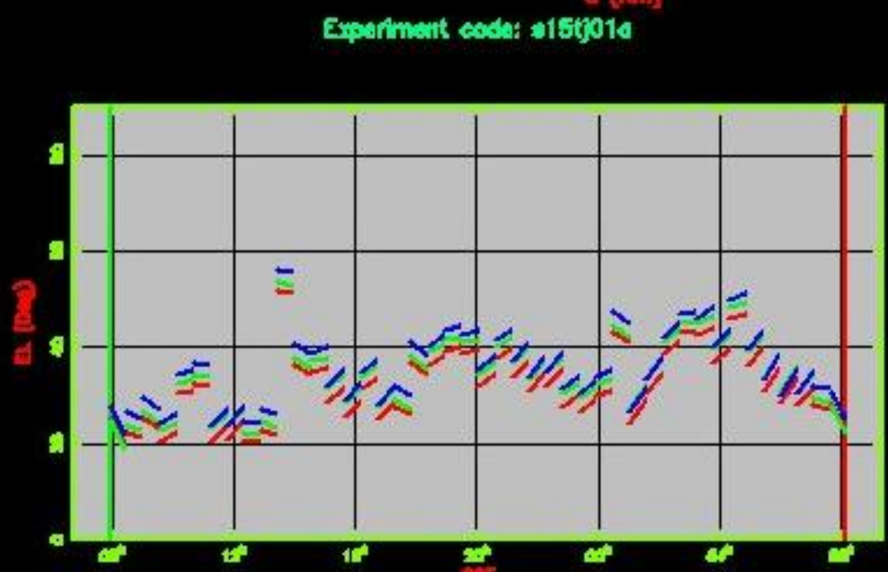
- Physical properties at 2-13mm wavelengths
  - flux densities, spectral index, compactness, populations etc.
- Provides high frequency VLBI calibrators

KVN Legacy Program

Pilot MASK observation related to ALMA







- 1st pilot MASK survey for sources for ALMA calibrators
  - KVN Calibrator Survey (single dish)
    & ALMA calibrator catalogs (Ed. Fomalont)
- 1st Observation : 20 Jan 2015
- 42 sources (-33° < dec < 0 °)
- Frequencies: simultaneous obs. at 7 & 3 mm
- Detections at 2 ~ 13 mm (22GHz – 130GHz)

ALMA Band

Freq. range 30-1000 GHz (0.3-10mm)

ALMA Band	Frequency Range (GHz)	Receiver Noise (K) over 80% of the RF band	Temperature (K) at any RF Frequency	To be produced by	Receiver Technology
1	31 - 45	17	26	tbd	HEMT
2	67 - 90	30	47	tbd	HEMT
3	84 - 116	37	60	HIA	SIS
4	125 - 163	51	82	NAOJ	SIS
5*	162 - 211	65	105	OSO	SIS
6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	385 - 500	196	292	NAOJ	SIS
9	602 - 720	175	261	NOVA	SIS
10	787 - 950	230	344	NAOJ	SIS

ALMA band matches KVN frequencies

tbd: to be decided
IRAM: Institut de Radio Astronomie Millimétrique (Grenoble, France)
HIA: Herzberg Institute of Astrophysics (Victoria, Canada)
NAOJ: National Astronomical Observatory of Japan (Mitaka, Japan)
NOVA: Nederlandse Onderzoekschool voor Astronomie (Groningen, the Netherlands)
NRAO: National Radio Astronomy Observatory (Charlottesville, USA)
OSO: Onsala Space Observatory/Chalmers University (Onsala, Sweden)
* EU FP6 receivers from Onsala

Sky Coverage

- Latitude ~ -23 deg
- Elevation limit ~ 3 deg

Northern source : Max length of observation (hours)

Declination	El > 10 deg	El > 15 deg	El > 20 deg	El > 30 deg
+55	2.7	-	-	-
+50	5.9	2.5	-	-
+40	7.0	5.8	4.3	-
+30	8.3	7.3	6.3	3.9
+20	9.2	8.4	7.5	5.7

(credit: Todd Hunter)

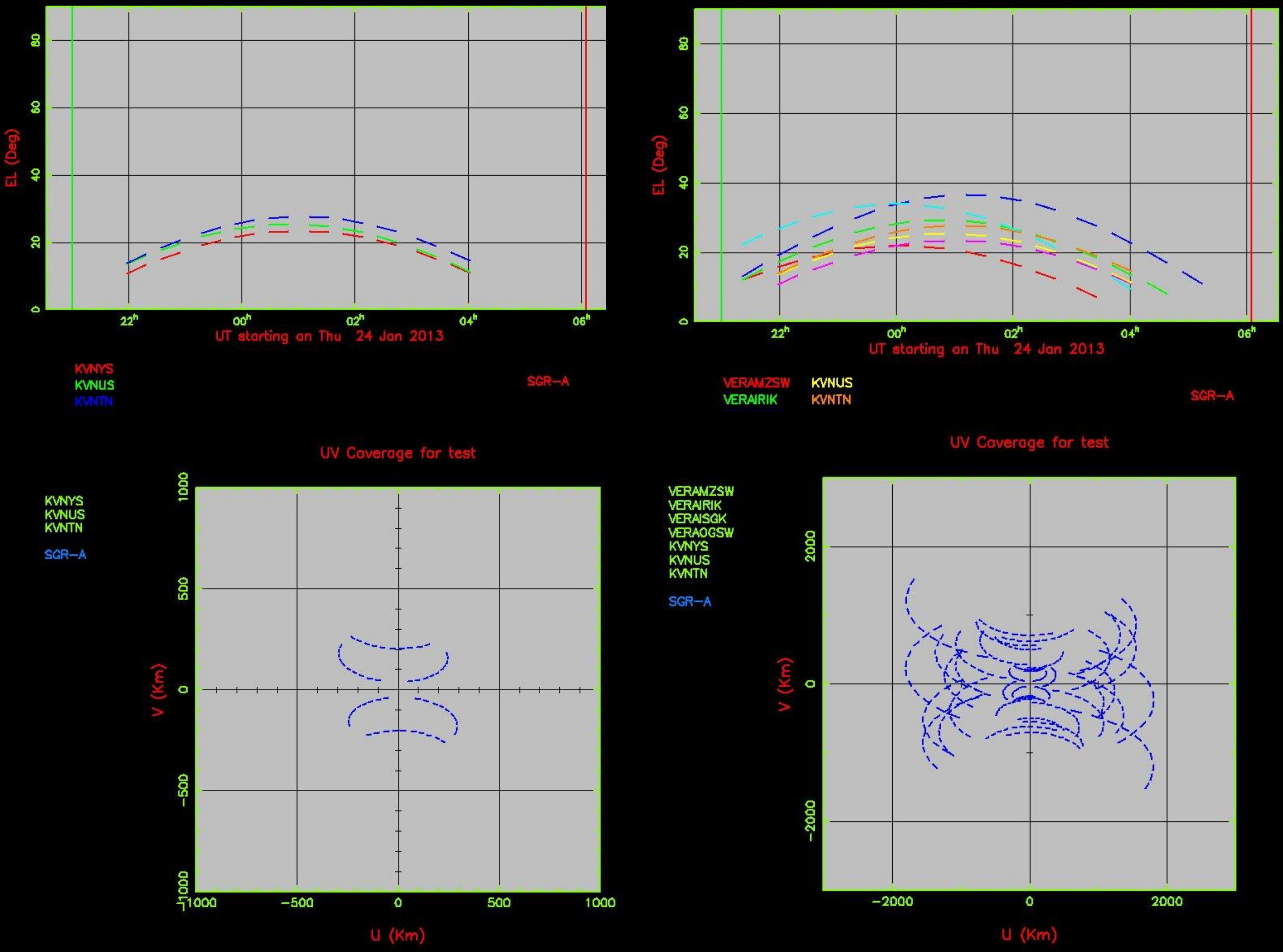
ALMA Resolution

16 km Max baseline (~ 10 mas)

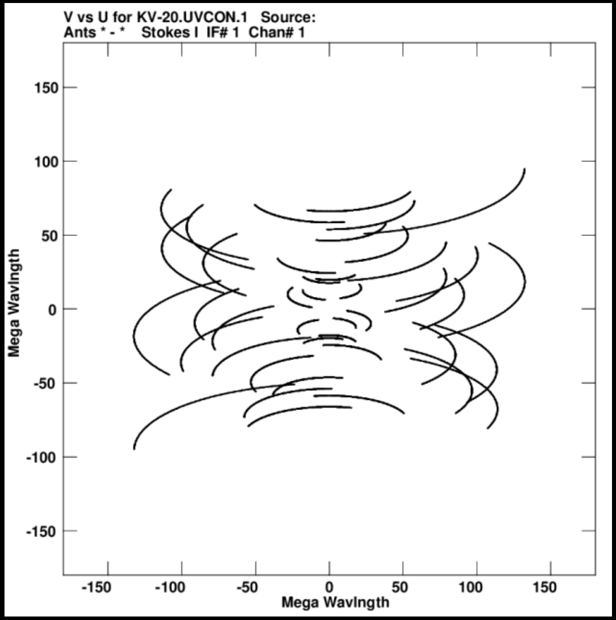
Configuration	Resolution / Frequency
Most compact ~150m	700” / 675GHz 4.8” / 110GHz
Most extended ~ 16km	6mas / 675GHz 37mas / 110GHz

Resolution match with the KVN (1~ 9 mas)

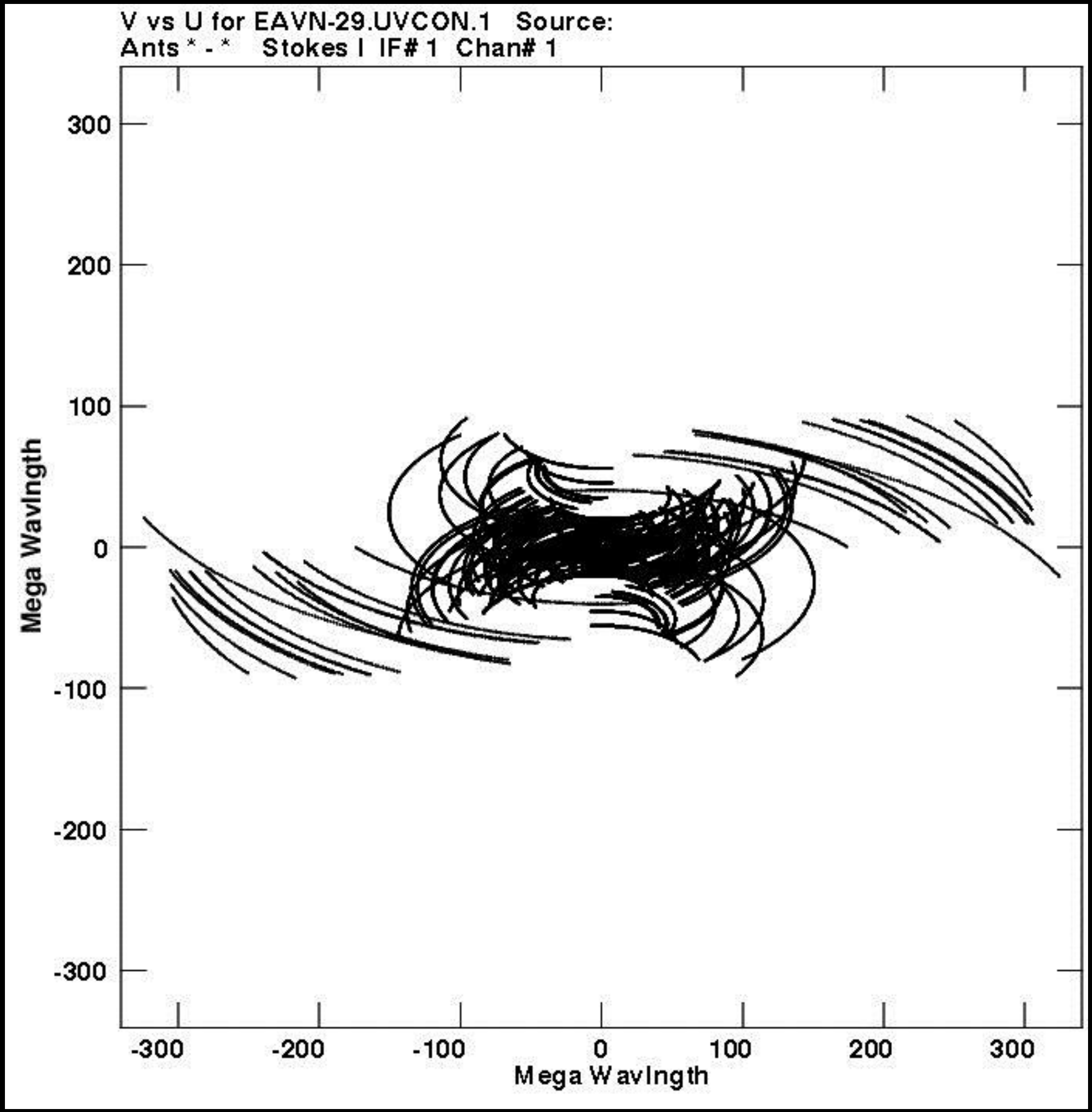
KVN SgrA* observation (24-25 Jan 2013)



KaVA (KVN+VERA)
(-20 deg @K)



EAVN
(-29 deg @K)



ALMA Resolution

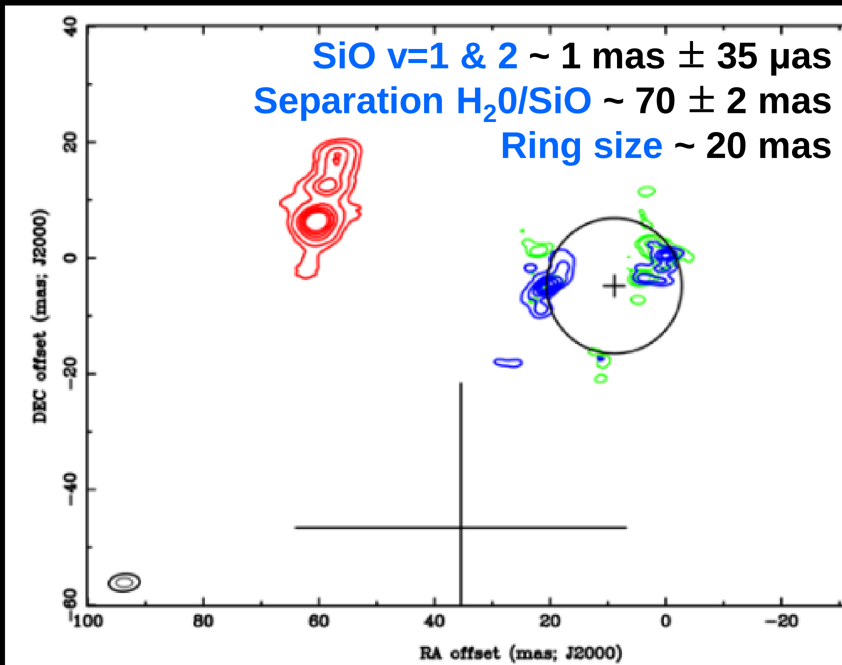
16 km Max baseline (~ 10 mas)

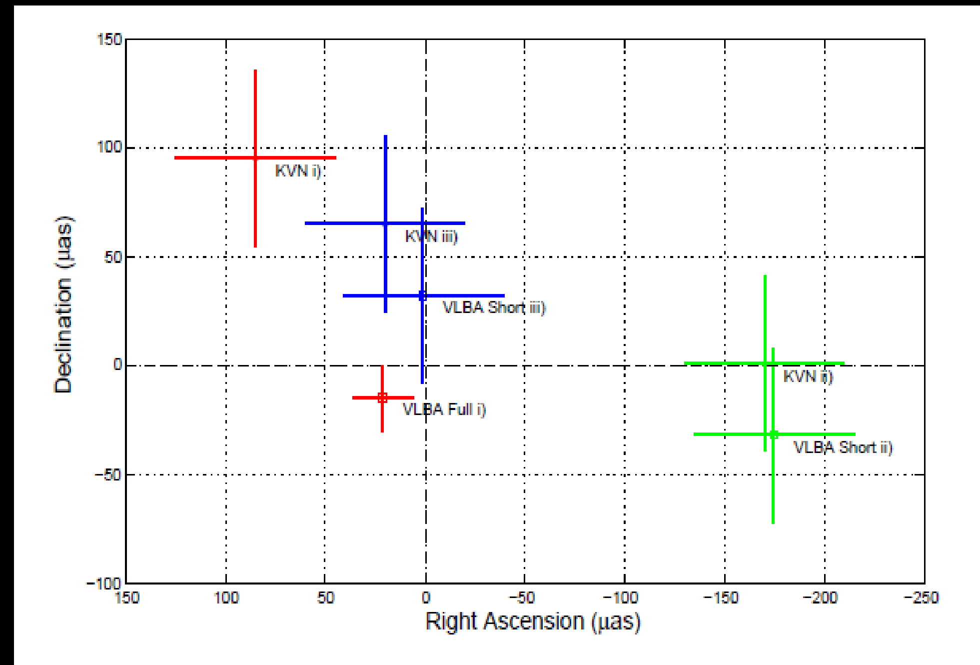
Configuration	Resolution / Frequency
Most compact ~150m	700” / 675GHz 4.8” / 110GHz
Most extended ~ 16km	6mas / 675GHz 37mas / 110GHz

- Spatial resolution of KVN (1~ 10 mas)

Two Main Reasons in VLBI Phase Referencing

2. Astrometry → high-precision astrometry at mm/sub-mm wavelengths

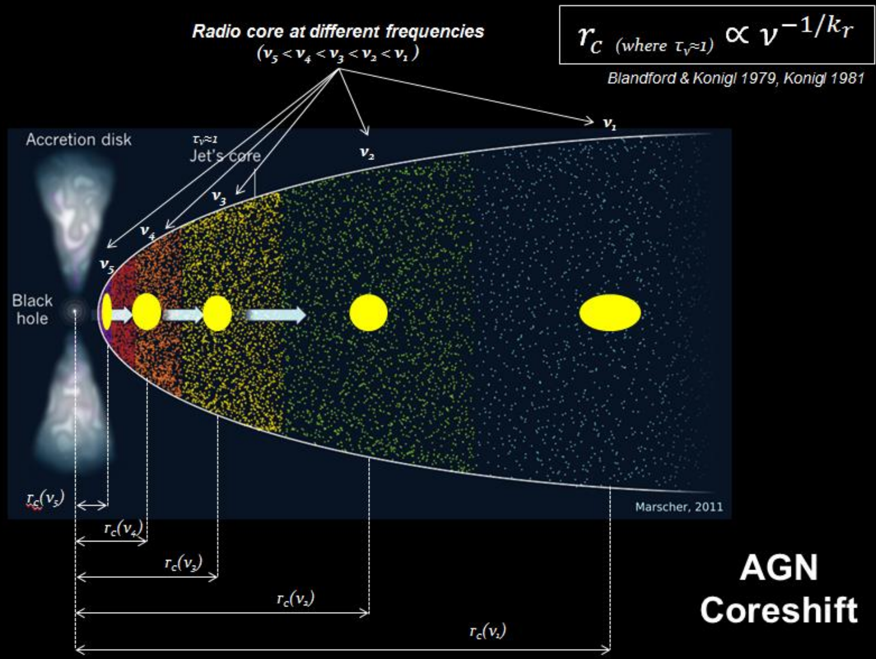


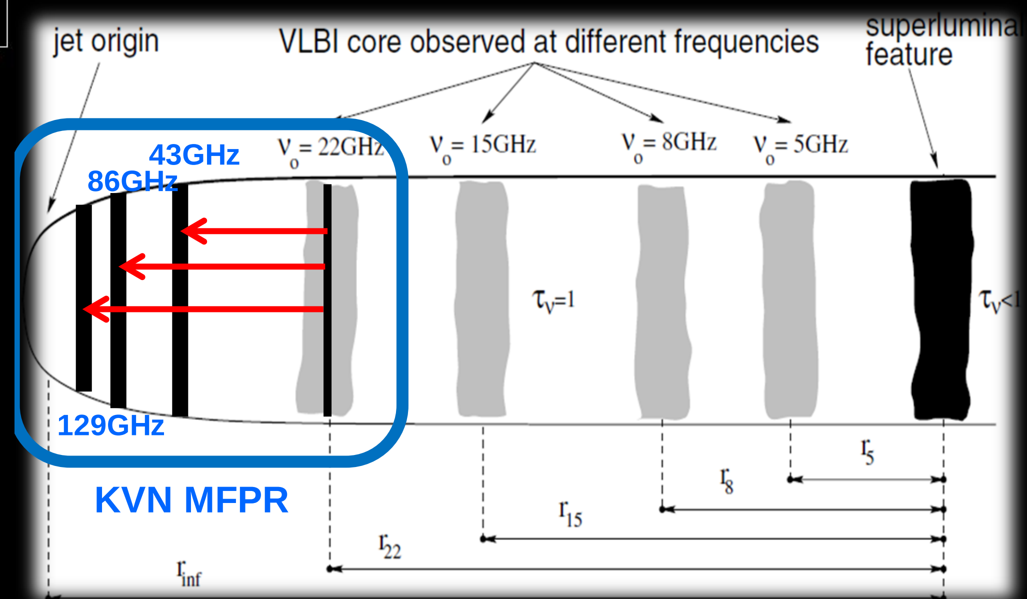


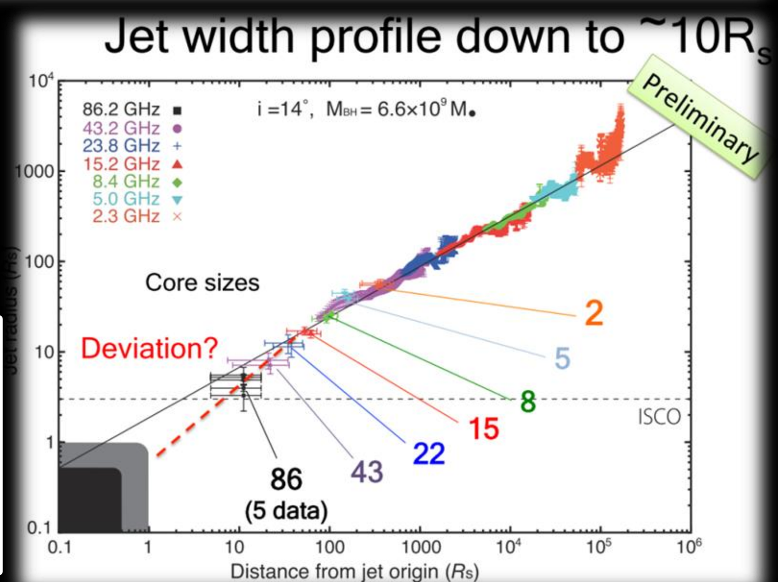
- Dodson et al. 2014
- Simultaneous observation of H_2O & SiO (v=1 & 2) maser lines for R Leo Minoris
- SiO maser phase referenced to H_2O maser

- Rioja et al. 2014
- Simultaneous 22/43GHz
  - 0854+213 w/ reference OJ287
  - 1.2deg away
- Core shift accuracy ~ 40 μas
- Consistent with VLBA within 1σ-error
- Structure blending effect should be considered
- Flux recovery ~ 94% using KVN SFPR

New Method in mm-VLBI Astrometry







Simultaneous multi-frequency observation

Perfect calibration to the troposphere

Ideal methods, especially mm/submm 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

1st Workshop on
Multi-Frequency VLBI Studies of AGN Core-Shift

- 18-19 Dec 2014 @ KASI, Korea
- ~30 participants
- Reported on EVN Newsletter #40
- Upcoming RadioNet3 ERATec WS related to global MF mm-VLBI system "Software Controlled operation and Implementation of Simultaneous Observations at mm-wave bands on Radio Telescopes"
  - 5-7 Oct 2015
  - Osservatorio Astronomico di Arcetri Florence, Italy

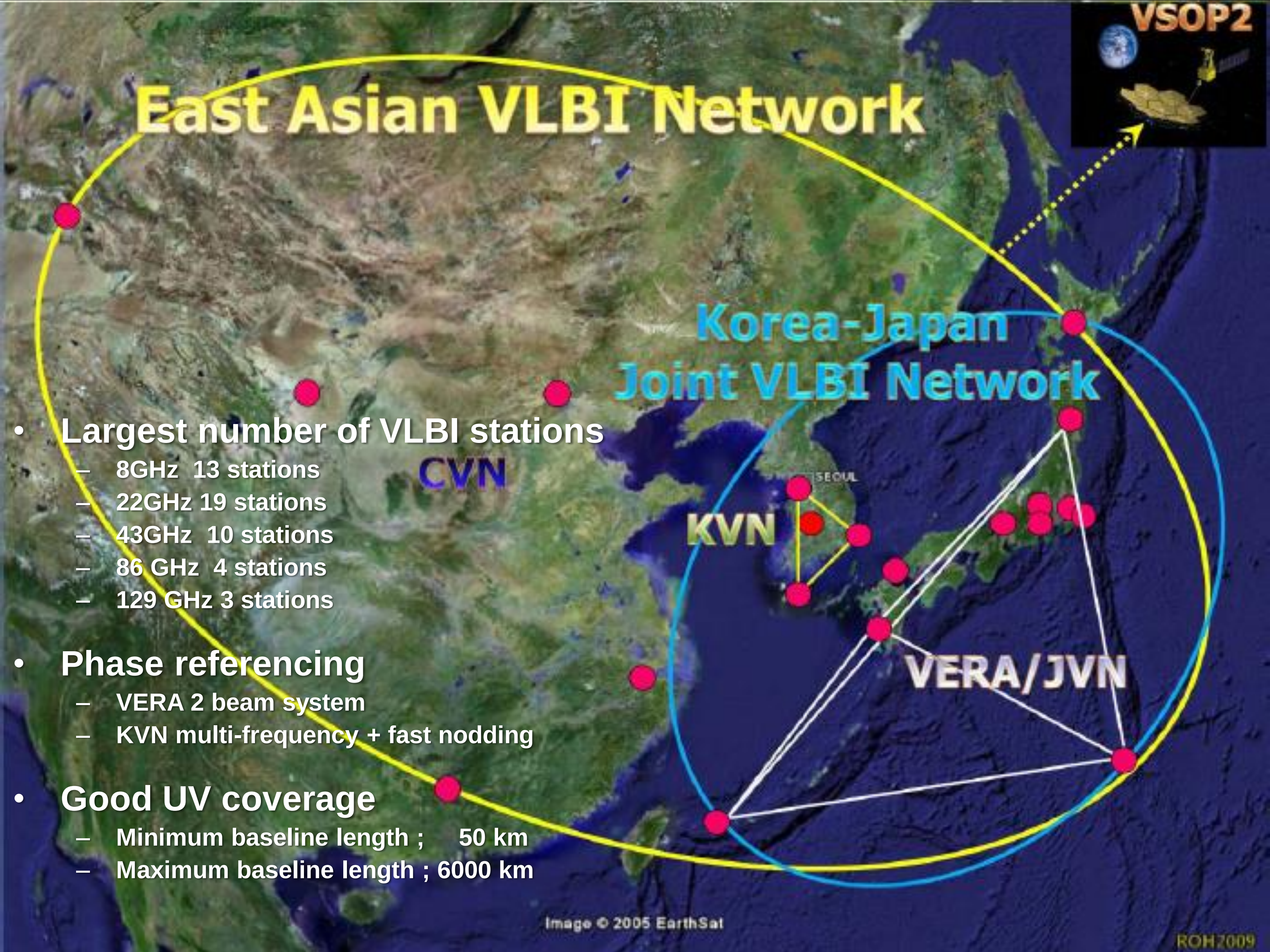
Global mm-VLBI Telescopes

with Multi-frequency system

Imaged by Taehyun Jung

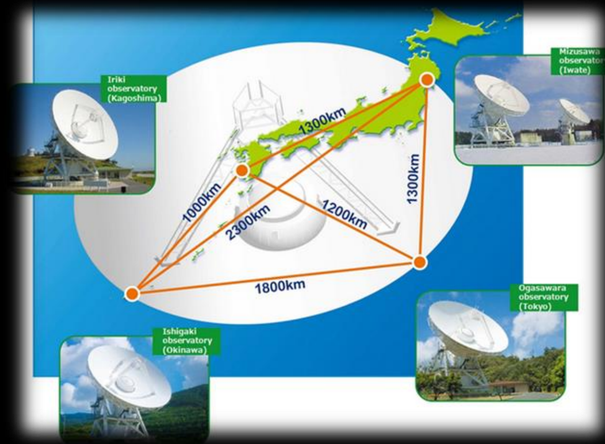
East Asian VLBI Network

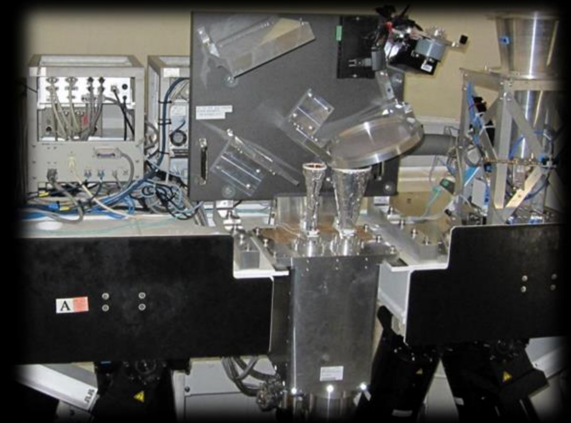
- Largest number of VLBI stations
  - 8GHz 13 stations
  - 22GHz 19 stations
  - 43GHz 10 stations
  - 86 GHz 4 stations
  - 129 GHz 3 stations
- Phase referencing
  - VERA 2 beam system
  - KVN multi-frequency + fast nodding
- Good UV coverage
  - Minimum baseline length ; 50 km
  - Maximum baseline length ; 6000 km



International Collaborations!!

VERA 20m. 22/43 Fringe Test 2014 June





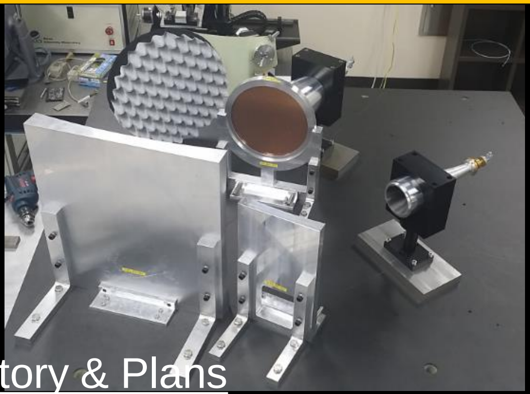
Yebes 40m
22/43/(86/129)
22/43 Installation
in 2014 Nov

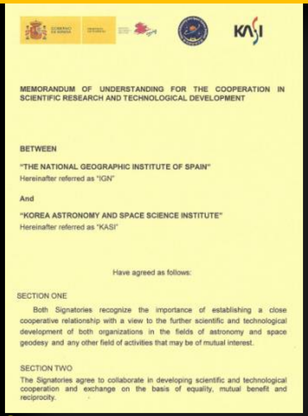
VLBA (MK) 25m
discussion on QO
22/43/86 (2014 May)

ATCA 22m x 6
43/86 Test in 2014 Sep

Noto or Sardinia in near future??

Quasi-Optics as a Powerful Tool of mm-VLBI Collaboration with Yebes 40m & VERA Mizusawa




MEMORANDUM OF UNDERSTANDING FOR THE COOPERATION IN SCIENTIFIC RESEARCH AND TECHNOLOGICAL DEVELOPMENT

BETWEEN

"THE NATIONAL GEOGRAPHIC INSTITUTE OF SPAIN"
Hereinafter referred as "IGN"

And

"KOREA ASTRONOMY AND SPACE SCIENCE INSTITUTE"
Hereinafter referred as "KASI"

Have agreed as follows:

SECTION ONE

Both Signatories recognize the importance of establishing a close cooperative relationship with a view to the further scientific and technological development of both organizations in the fields of astronomy and space geodesy and any other field of activities that may be of mutual interest.

SECTION TWO

The Signatories agree to collaborate in developing scientific and technological cooperation and exchange on the basis of equality, mutual benefit and reciprocity.

History & Plans

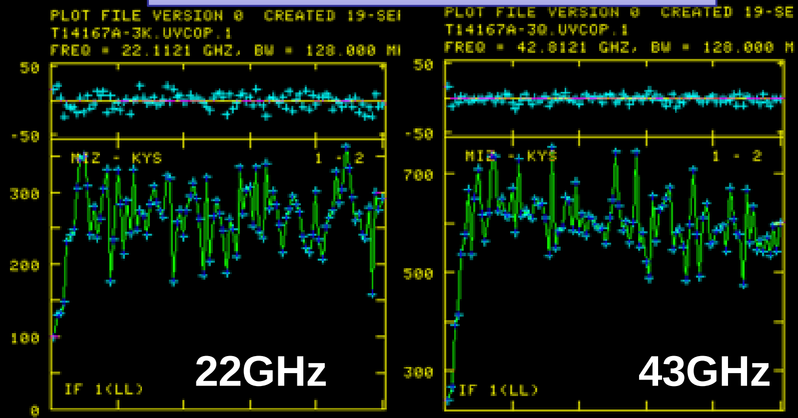
- 2011 Nov. : K/Q/W QO discussion
- 2014 Jan-Aug : QO design
- 2014 Jun : KASI-IGN MOU
- 2014 Sep : Manufacture
- 2014 Oct : Shipping to Yebes
- 2014 Nov : Installation & Initial Test
- 2015 Jan : First light of QO at K/Q

History & Plans

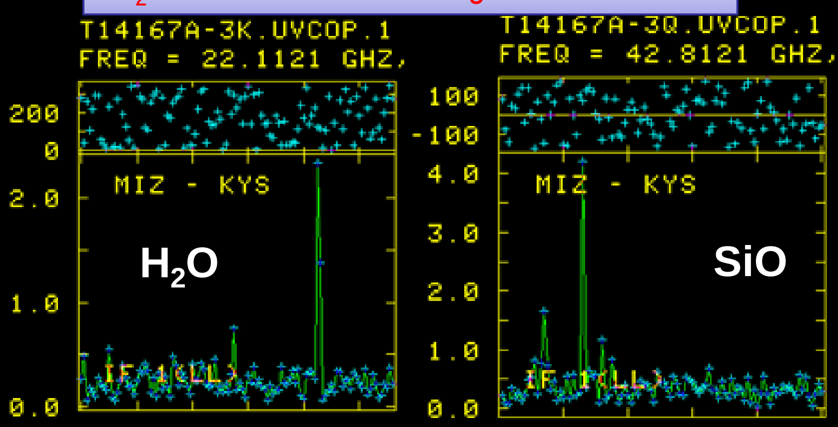
- 2013 Nov : Manufacture
- 2013 Dec. : Shipping & Installation
- 2014 Jun : K/Q VLBI fringe test
- 2014 Sep : Fringe Detection
- 2014 Dec : Science verification test
- 2015 VERA QO for Miz & Iri stations

Success on QO test outside of KVN

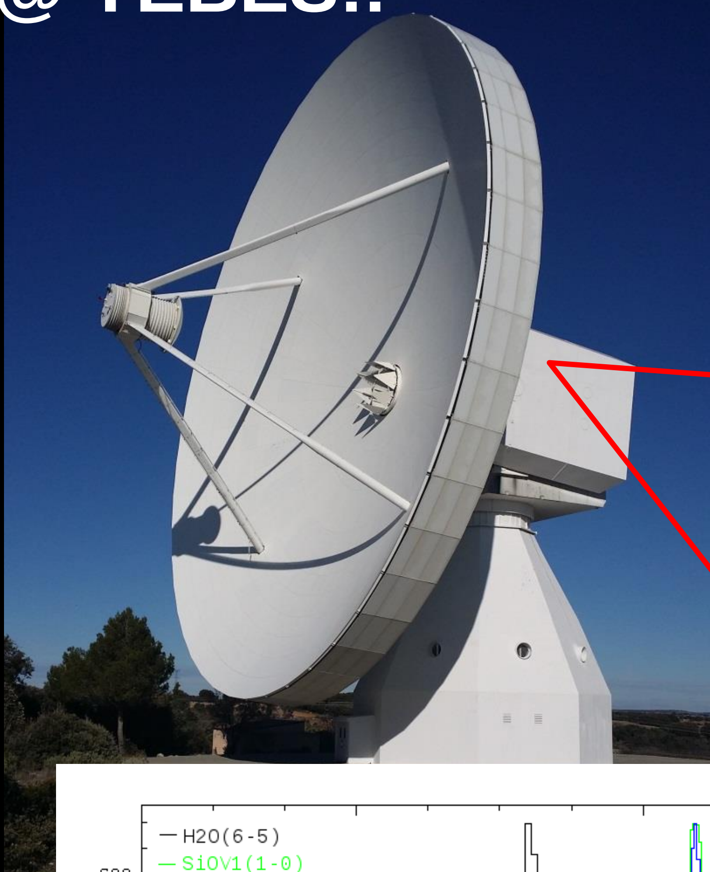
K/Q simultaneous fringes of OJ287

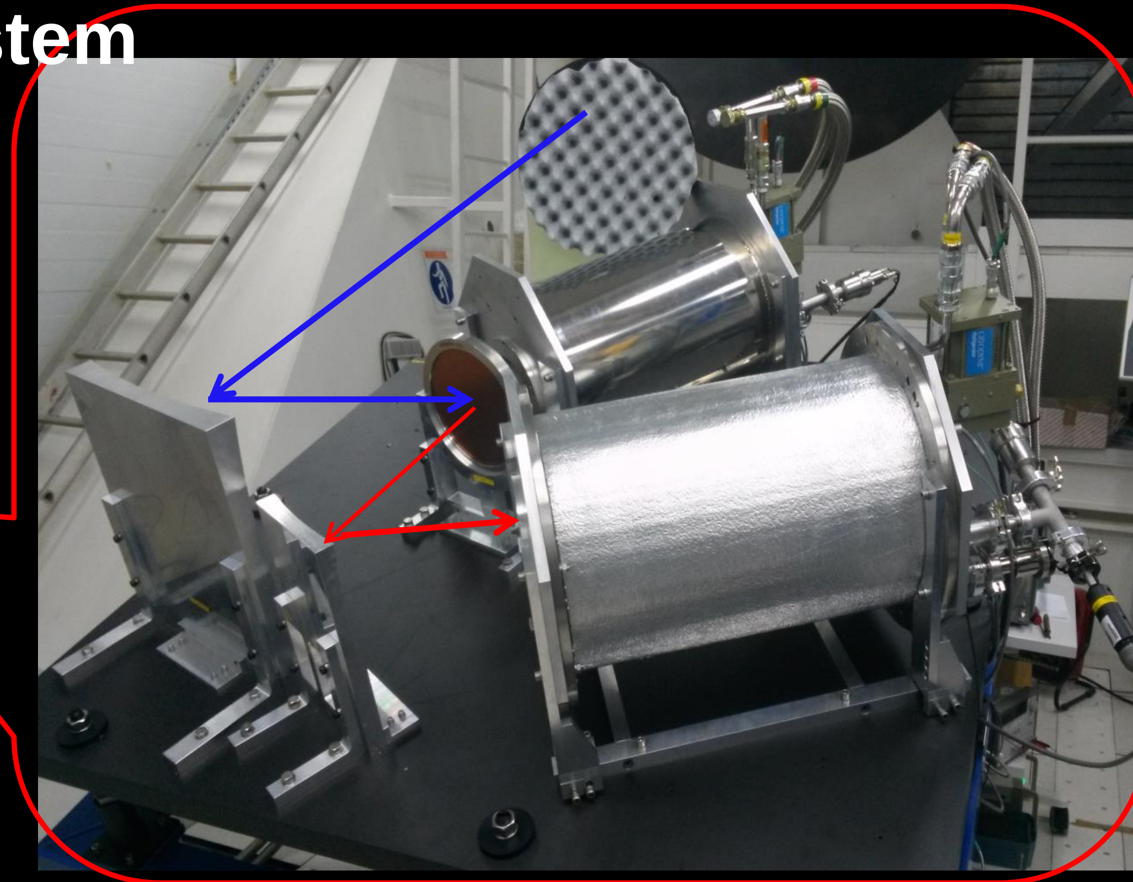


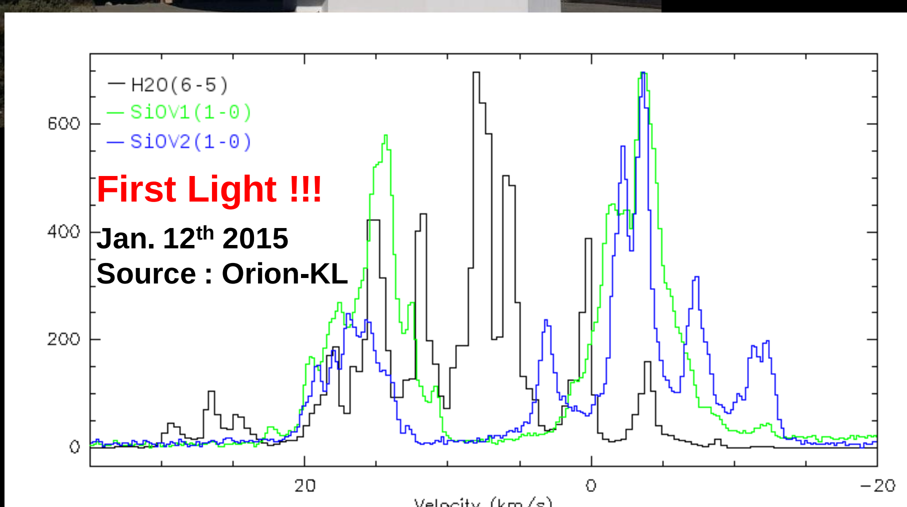
H_2O/SiO Simultaneous fringes of ORION-KL

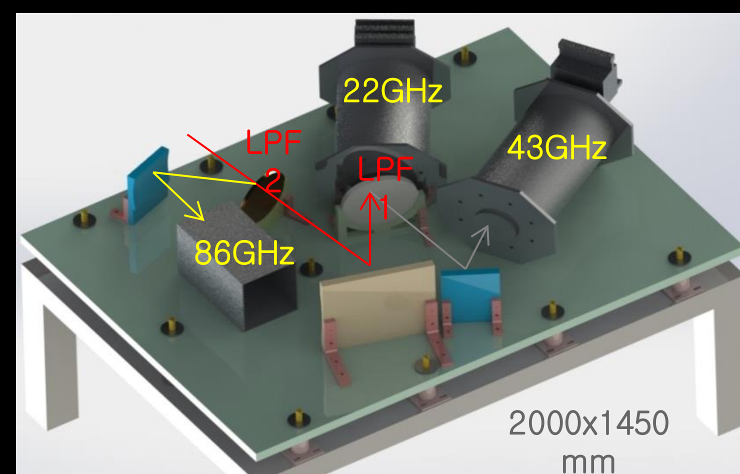


Multi-Frequency System @ YEBES!!



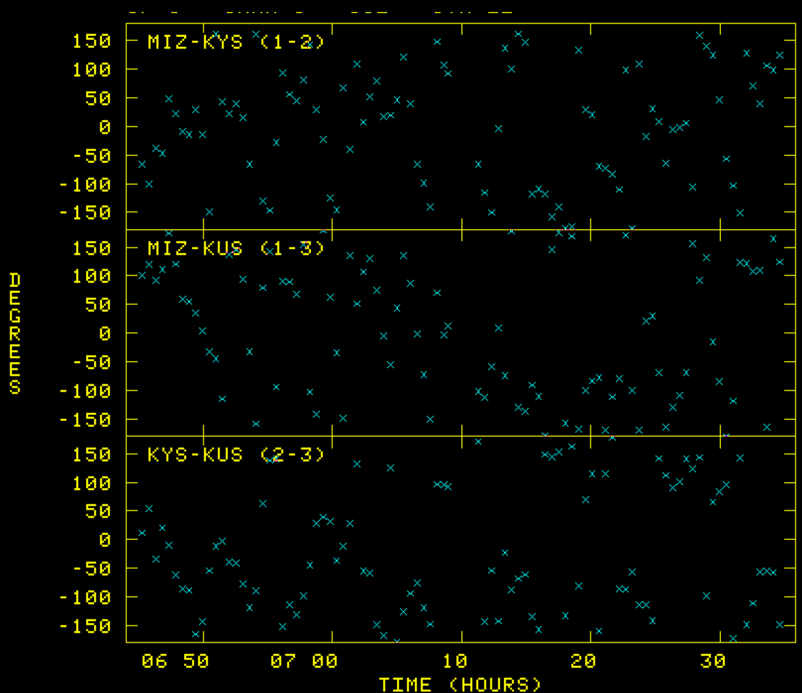




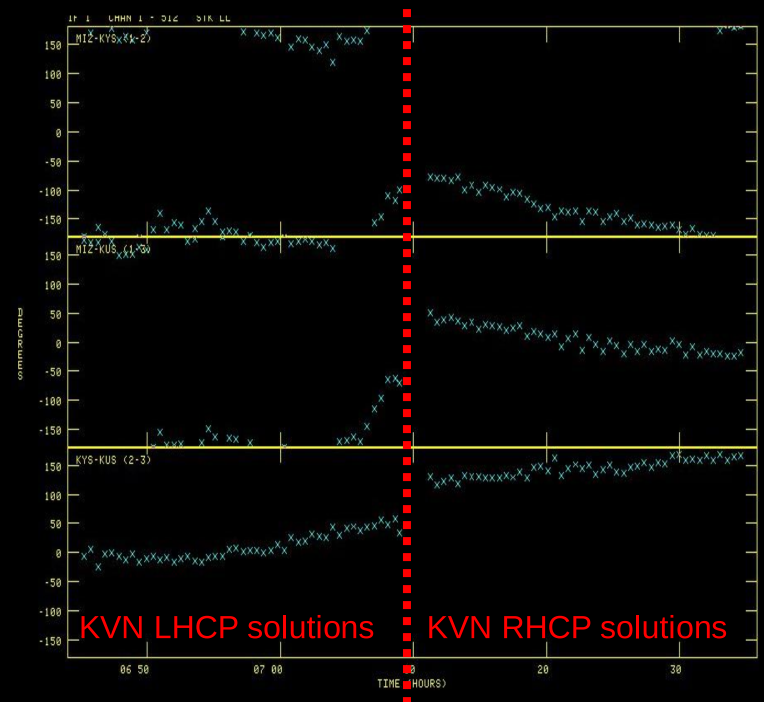


Phase Correction with QO systems (K→Q, OJ287)

Q-band Visibility Phase
No calibration applied



Q-band Visibility Phase
Calibrated by K-band Phase Solutions



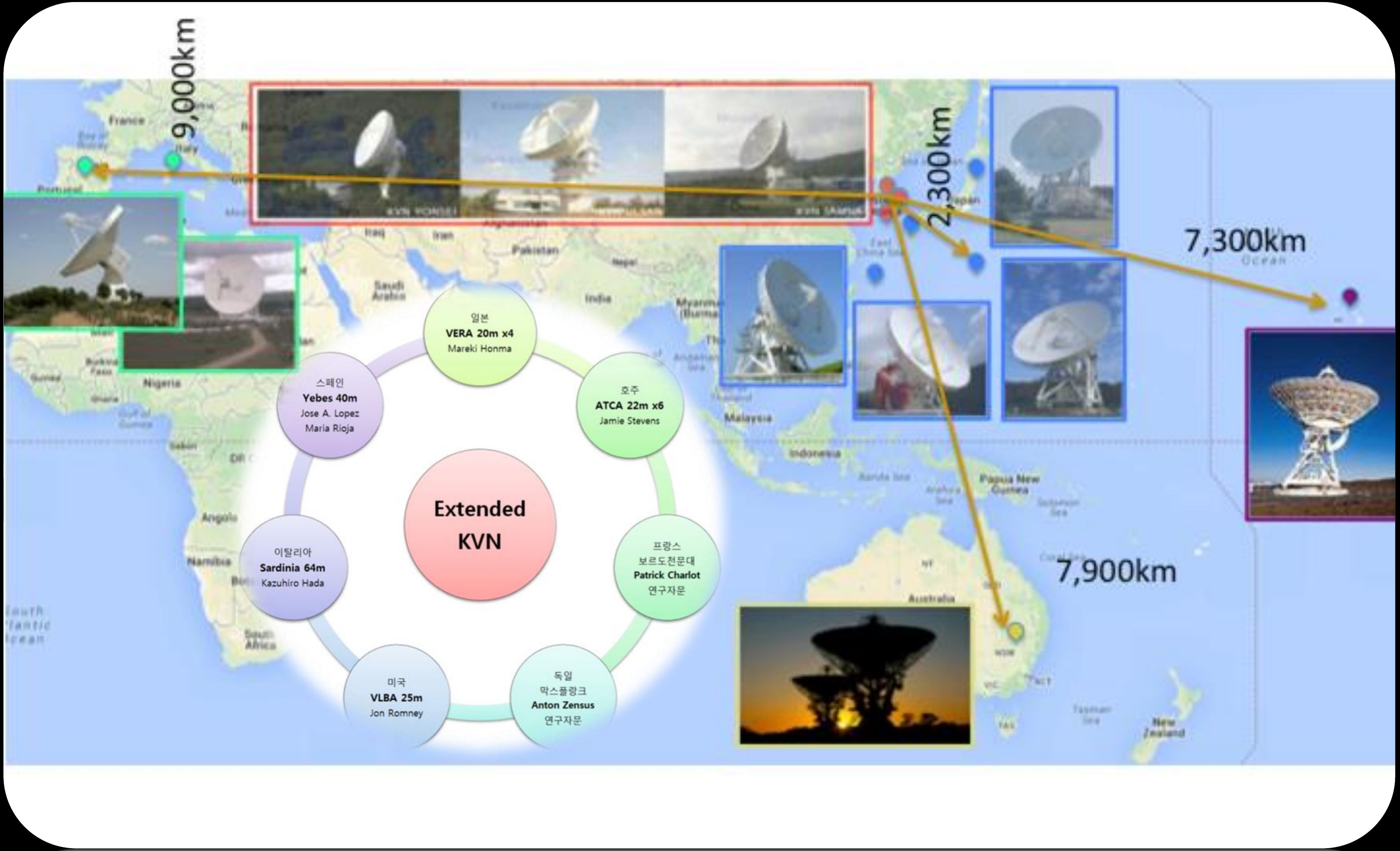
- K-band fringe phase solutions of OJ287 were applied to calibrate Q-band data
- Visibility phase of Q-band calibrated by K-band shows more stable phase than raw data although there are high phase rates at MIZ related baselines
  → The feasibility of K/Q simultaneous observing system has been demonstrated !!

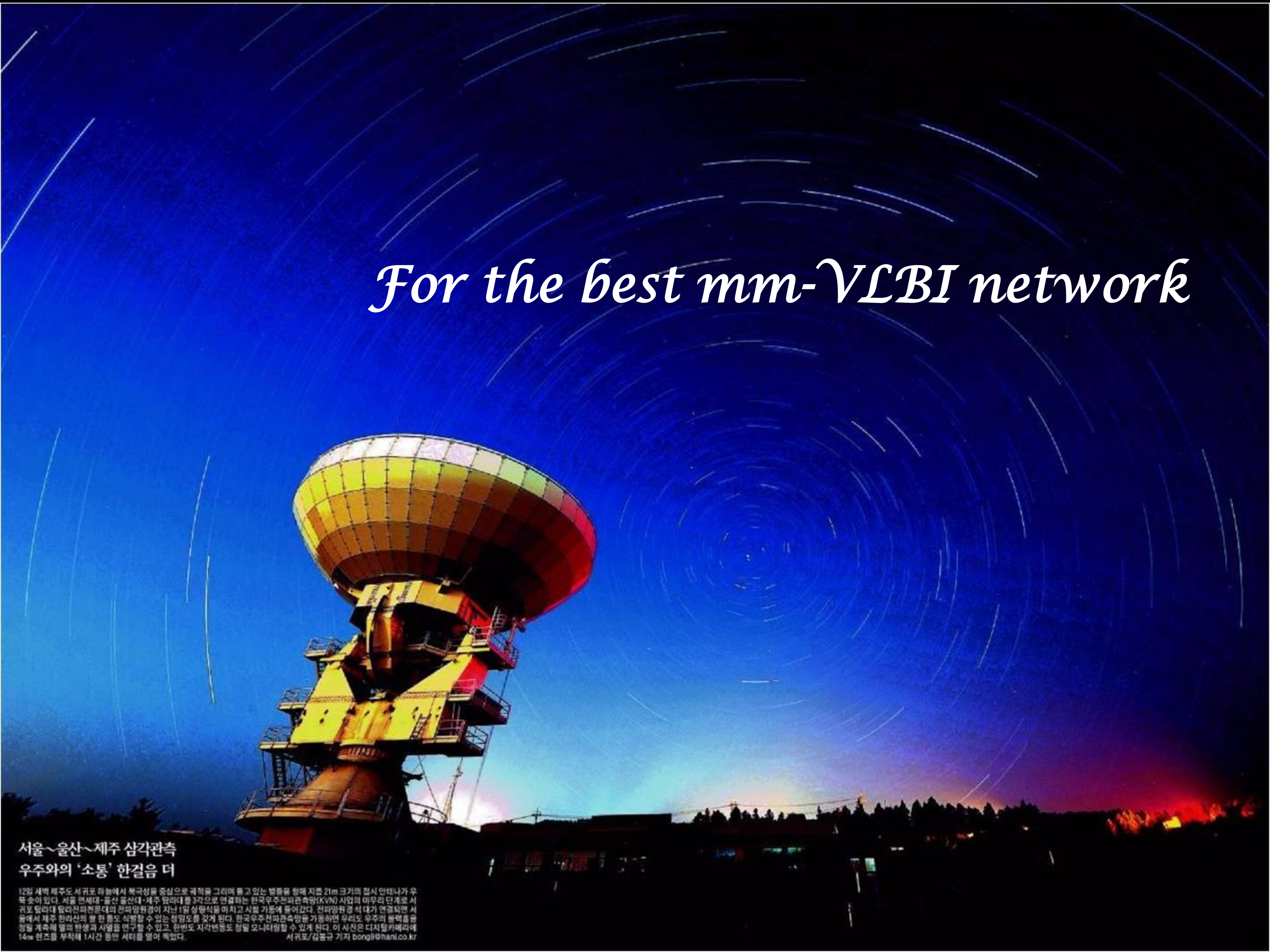
- Science demonstrations has been conducted on be half of KaVA science sub-working group

Better Resolution & More Sensitivity with Global Multi-Frequency System

because it's Simple & Powerful

more observing time, multi-frequency data, tropospheric calibration




For the best mm-VLBI network
서울~울산~제주 삼각관측
우주와의 '소통' 한걸음 더