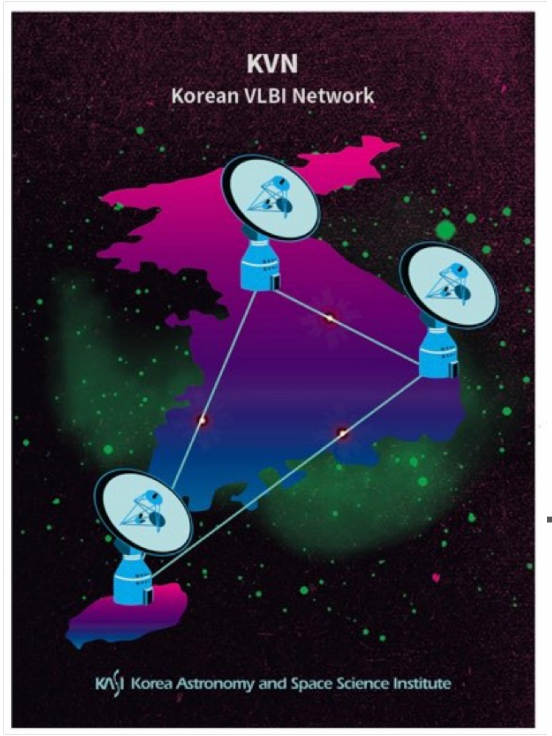
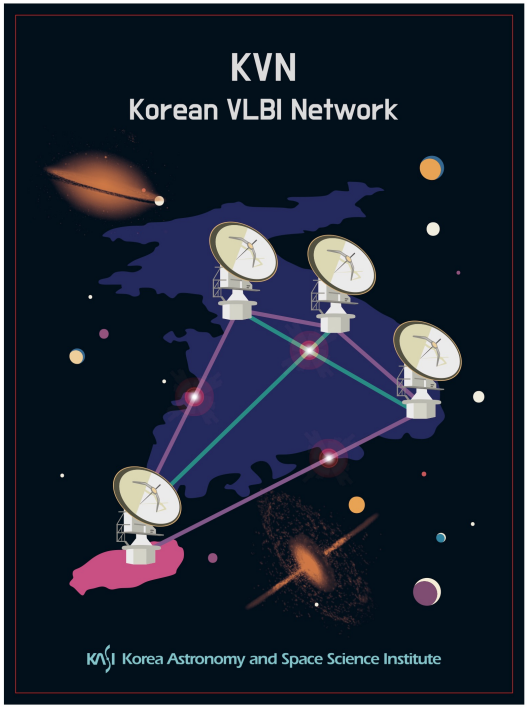
Enhancing Millimeter-wavelength VLBI Observations
The Extended Korean VLBI Network
- Current & Future -



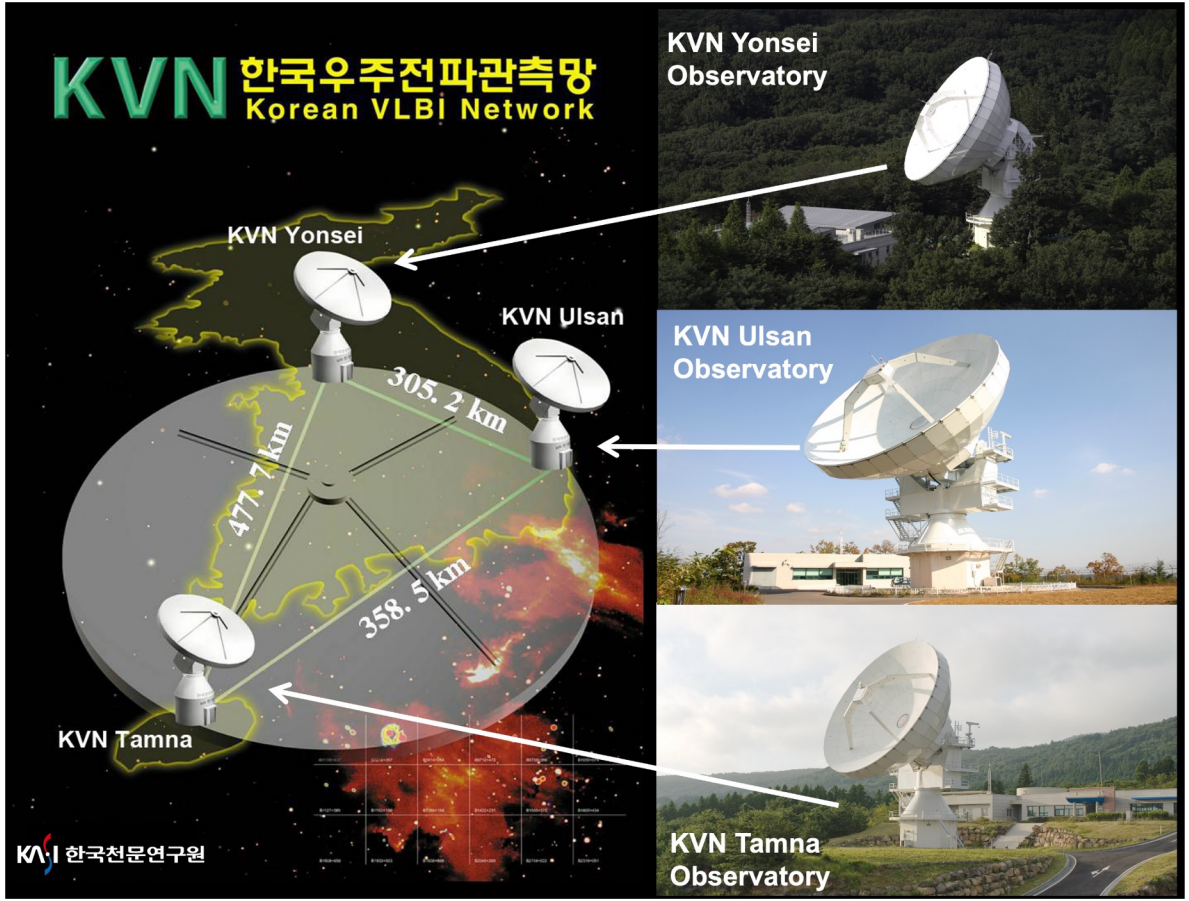


Taehyun Jung & Do-Young Byun
on behalf of KVN Team

KASI 한국천문연구원
Korea Astronomy & Space Science Institute

Survey Science Group Workshop 2024 @ High1 Resort
30 JAN 2024

Korean VLBI Network



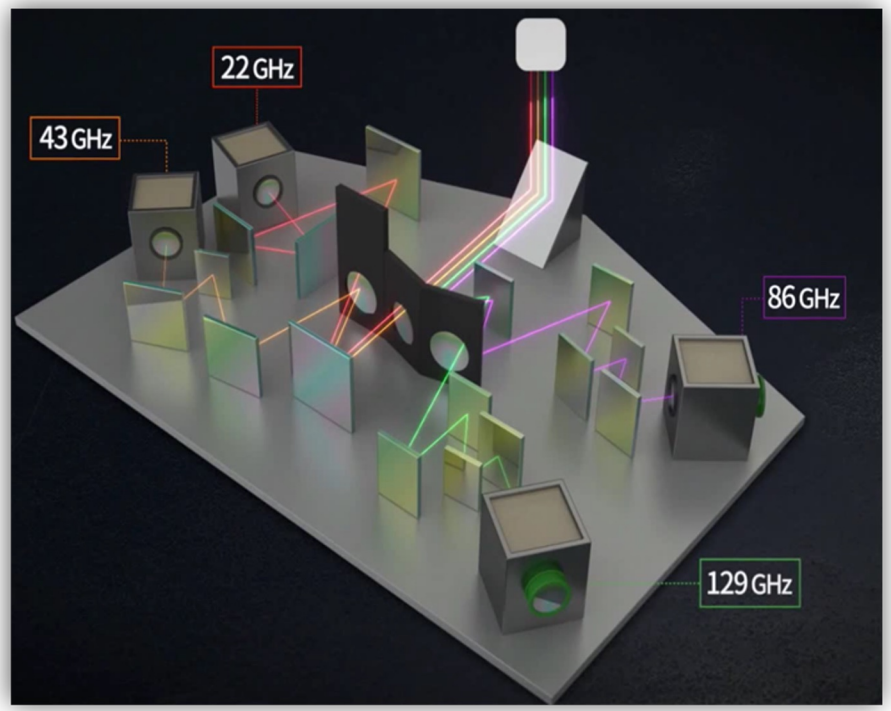
- **First simultaneous multi-frequency (22/43/86/129 GHz) receiving system**
- **Three 21m antennas**
- **Pointing accuracy**
  ~ < 3 arcseconds in RMS
- **Aperture efficiency**
  ~ 30 ~ 80 % @ 22 ~ 129 GHz

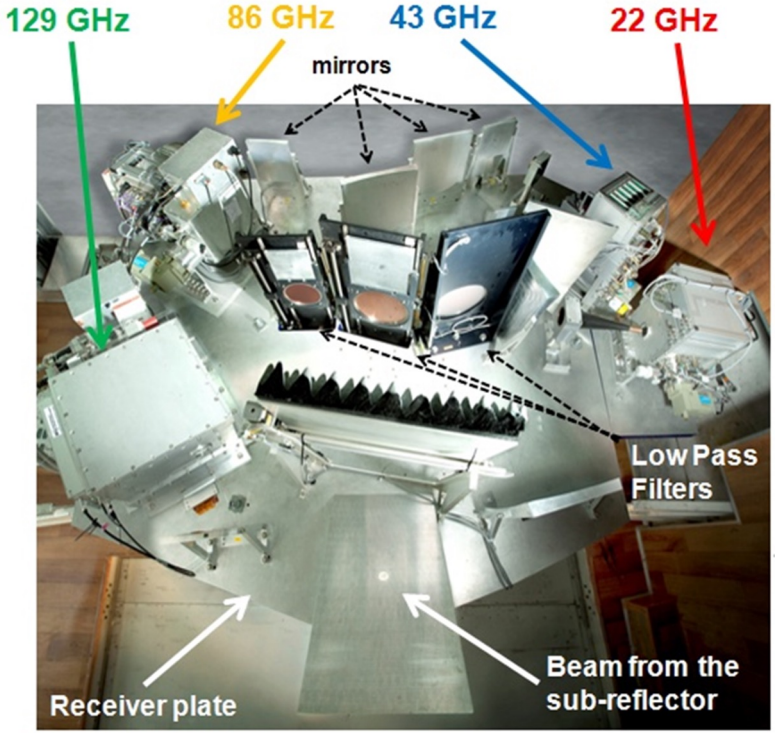
Main reflector (Axisymmetric Paraboloid)	Parameters
Diameter	D = 21.03 m
Focal length	f = 6.78 m
Focal ratio	f/D = 0.32
Panels manufacturing accuracy	65 μm
Alignment surface accuracy	50–54 μm
Sub-reflector (Hyperboloid) diameter	**Parameters**
Diameter	d = 2.25 m
Manufacturing surface accuracy	50 μm
Expected total surface accuracy	124 μm at EL 48°
Slewing speed	3 °/sec
Slewing acceleration	3 °/sec^2
Operating range	Az.: ±270°, El.: 0°–90°

※ KVN status report
→ http://kvn.kasi.re.kr → “status report”

KVN Receiver

Simultaneous Multi-Frequency Receiving System



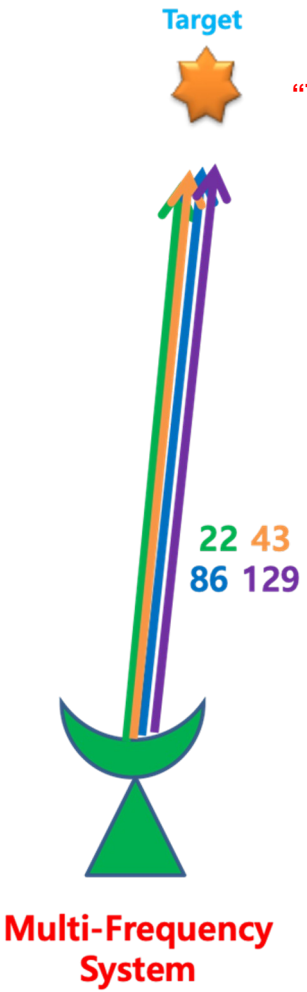


Band	K	Q	W	D
Freq. Range	18 - 26	35 - 50	85 - 116	125-142
Trx (K)	20-30	20-30	50-80	60-80

KVN 4CH Receiver
(Han et al. 2008, 2013)

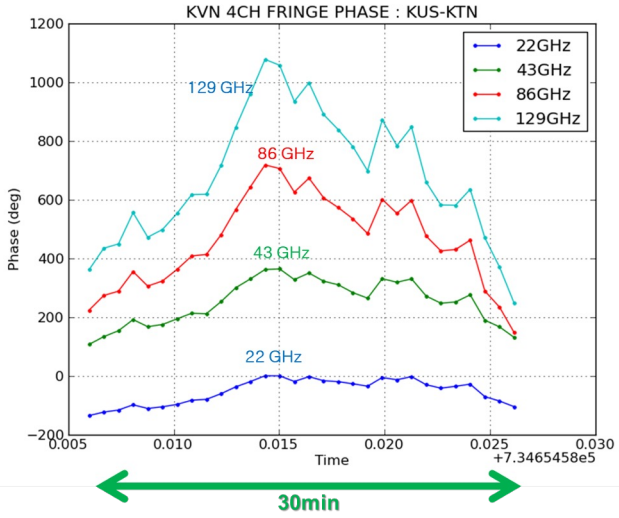
All LHCP & RHCP

Performance of KVN's Simultaneous MF System

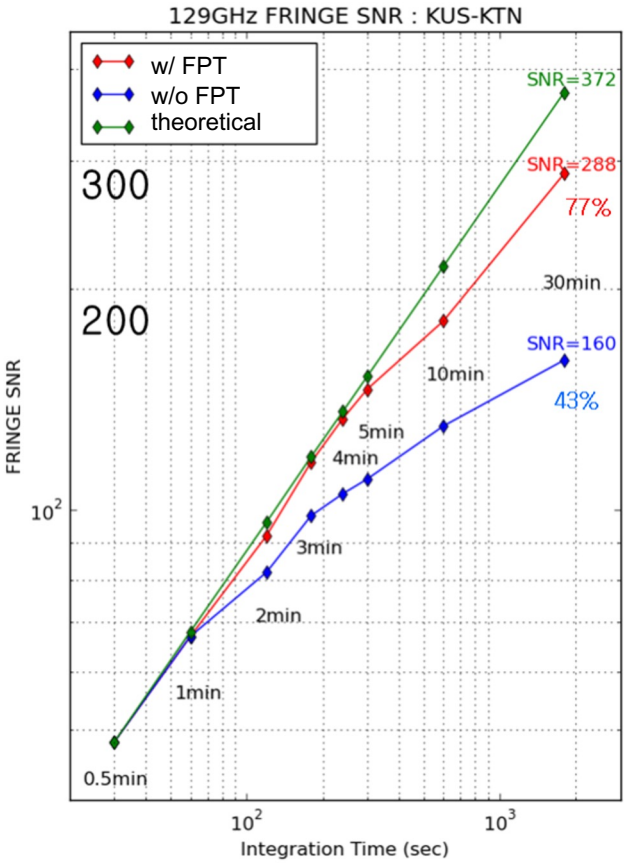


"Target source = Calibrator source"

- Once Source is detected at lower frequencies
- No observing time loss
- No calibrator issue
- No coherent loss (same sky position)

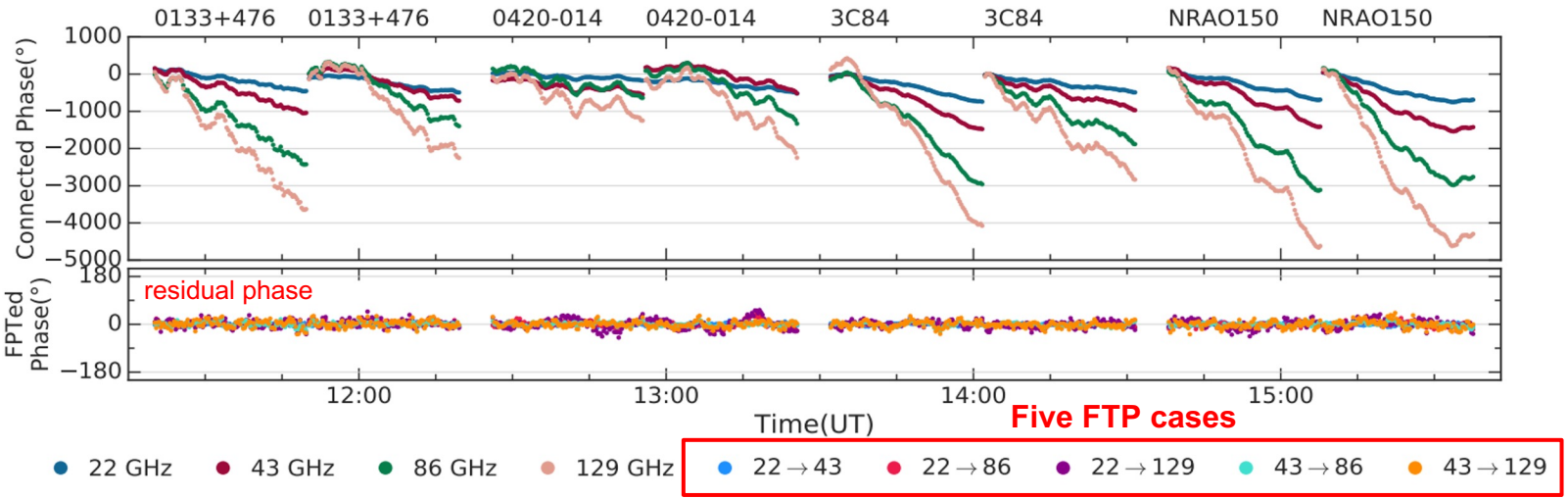


C_eff	22 GHz	43 GHz	86 GHz	129 GHz
22 GHz	-	0.97	0.91	0.88
43 GHz	0.97	-	0.97	0.96
86 GHz	0.91	0.97	-	0.99
129 GHz	0.88	0.96	0.99	-



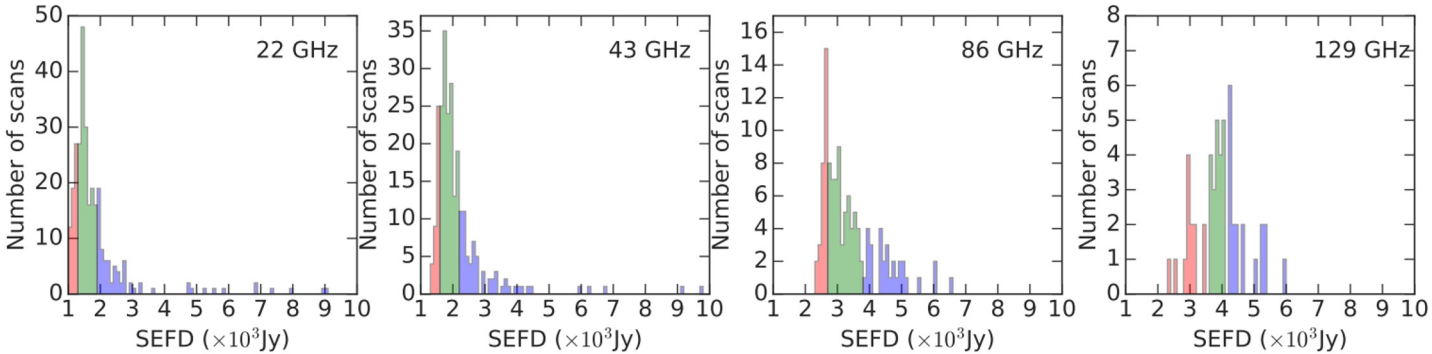
(target source: 3C 279)

FPT: Phase Solution Analysis (1)



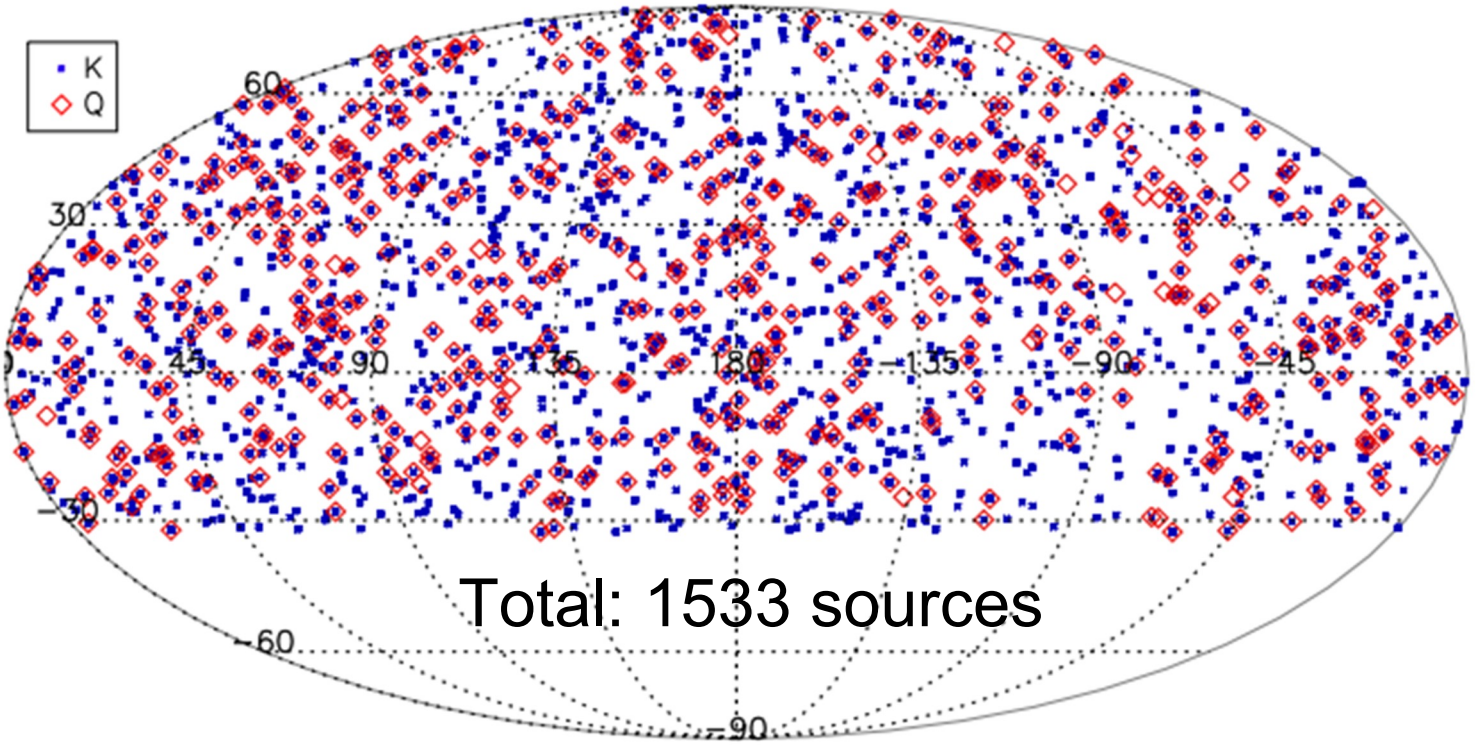
SEFD Distribution

Atmospheric condition
(G) good (25%)
(T) typical (50%)
(W) worse (25%)



Multi-frequency AGN Survey with KVN

MASK Sample: 1533 sources from KVN SD (>100 mJy at 22 GHz)



Simultaneous Multi-frequency VLBI Catalogue at 22/43/86/129 GHz

MASK Detection Statistics

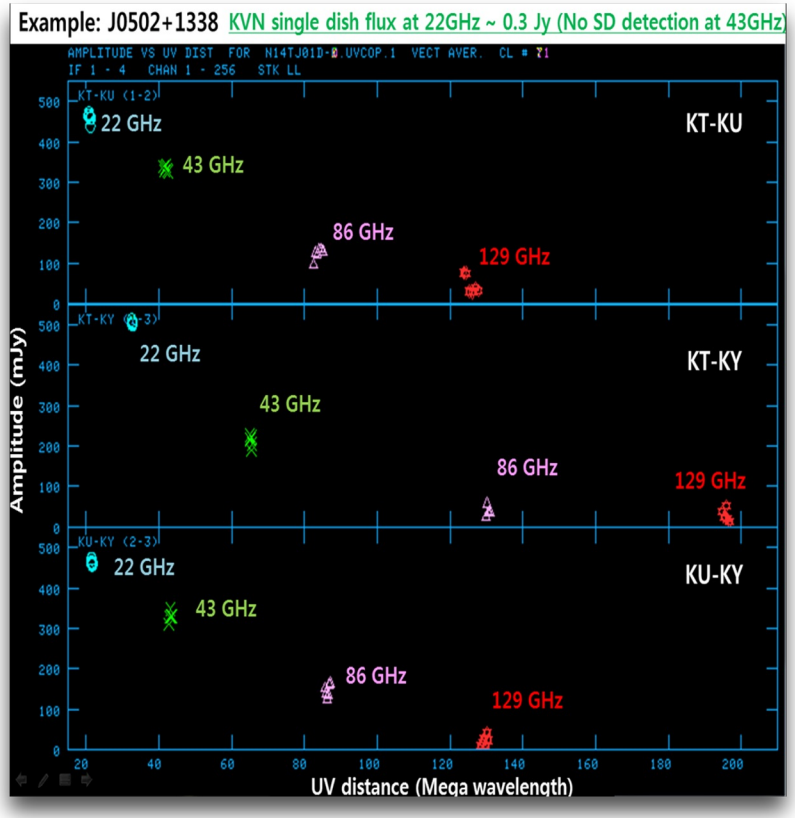
- Total number of sources (processed) : 1,525
- **Detection (K-22GHz, Q-43GHz, W-86GHz, D-129GHz)**
  - 22GHz self detection : 1,381 (91%)
  - 43GHz self detection : 1,082 (71%)

[K-band FPT]	**[Q-band FPT]**
K→Q : 1,091 (72%)	Q→W: 580 (38%)
K→W: 683 (45%)	Q→D: 329 (22%)
K→D : 330 (22%)	

thjung — kvnuser@KVNAOC: /home/KVN/Resource/Vex/2019a — vim mask-detec.txt — 93×45

~ — kvnuser@KVNAOC: /home/KVN/Resource/Vex/2019a — vim mask-detec.txt

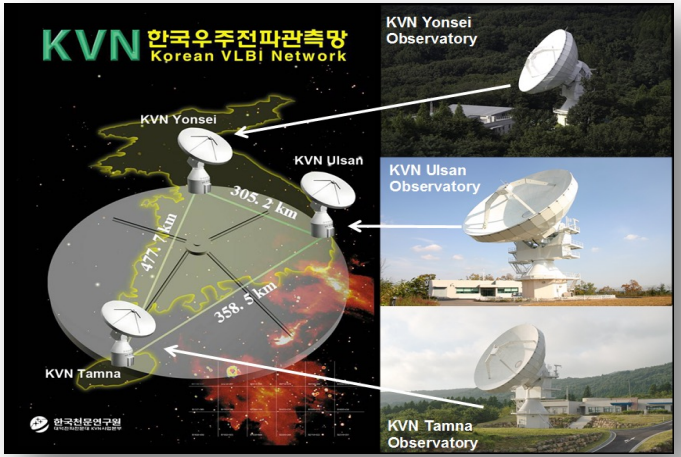
1	J0001-1551	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	s18tj01f
2	J0006-0623	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	s16tj02c
3	J0006-0623	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	s16tj02s
4	J0008-2339	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	s18tj01a
5	J0008-2339	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	s18tj02x
6	J0008+6837	TRUE	TRUE	TRUE	FALSE	TRUE	FALSE	FALSE	s18tj02a
7	J0009+4001	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	s18tj02a
8	J0010-2157	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	s18tj01f
9	J0010+1058	TRUE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	s16tj02a
10	J0010+1058	TRUE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	s16tj02l
11	J0010+1058	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	s16tj02s
12	J0011-2612	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	s18tj01a
13	J0011+0823	TRUE	TRUE	TRUE	FALSE	TRUE	FALSE	FALSE	s18tj02a
14	J0011+7045	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	s18tj02s
15	J0012+3353	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	s18tj02a
16	J0013+1910	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	s18tj02c
17	J0013+4051	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	s16tj02a
18	J0013+4051	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	s16tj02l
19	J0014+6117	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	s16tj02c
20	J0014+6117	TRUE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	s16tj02s
21	J0016-0015	TRUE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	s18tj01x
22	J0016-0015	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	s18tj02y
23	J0017-0512	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	s18tj01x
24	J0017+5312	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	s18tj02c
25	J0017+8135	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	s18tj02s
26	J0019+7327	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	s16tj02a



세계 최초 4채널 동시관측 시스템

2011년 교육과학기술부 과학기술창의상 대통령상 & 국제특허

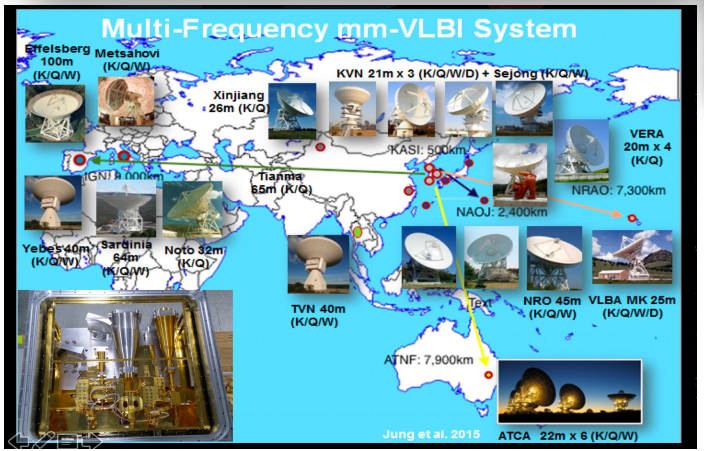
"KVN style"로 불리며
세계 밀리미터 전파간섭계 표준선도

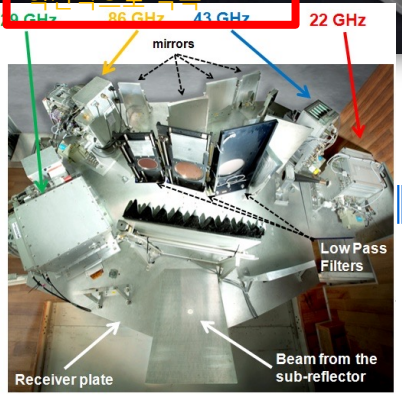




밀리미터 VLBI 관측의 한계(대기에 의한 오차)를 독자 개발한 시스템으로 가장 혁신적으로 극복



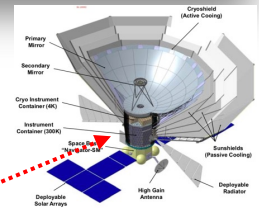






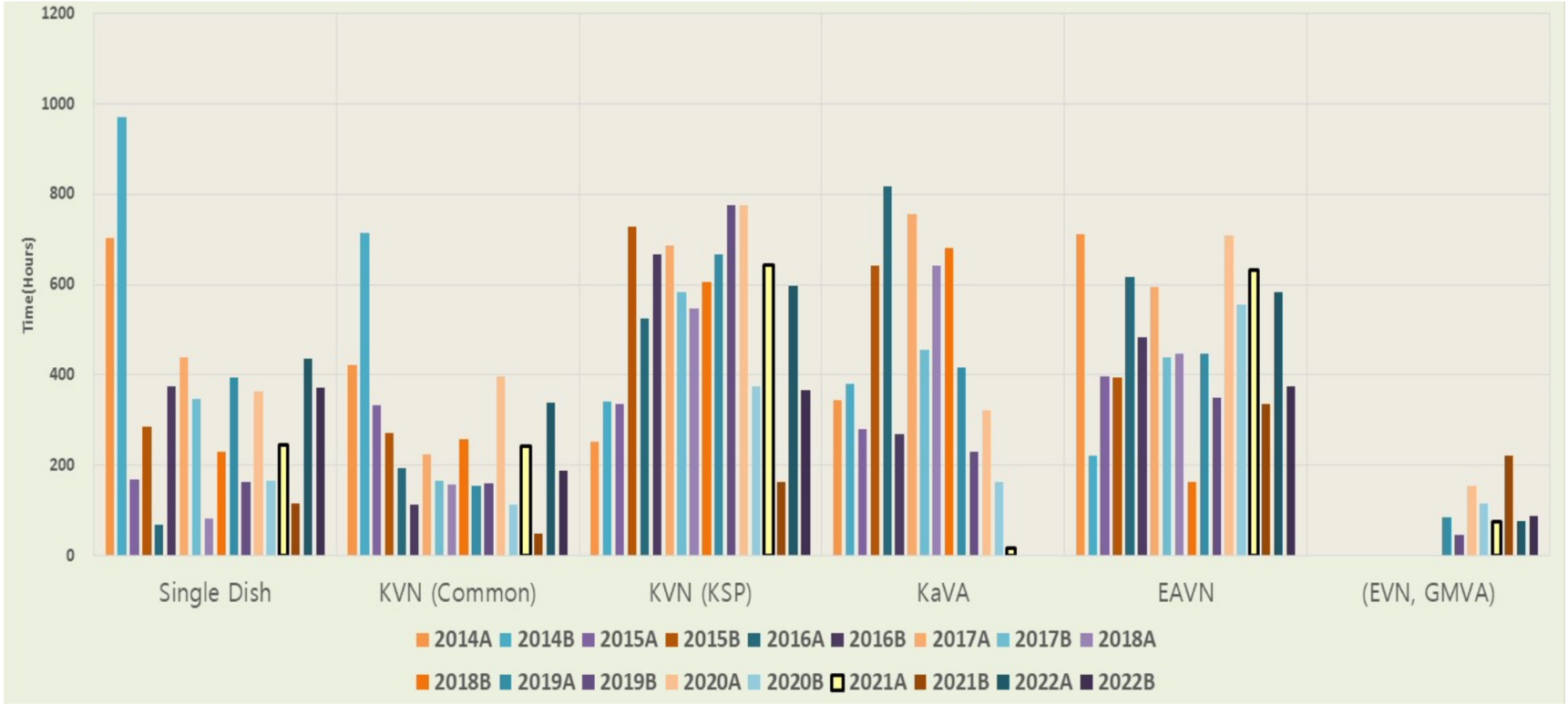
초소형 3채널 동시관측 시스템

2018년 NST 우수연구성과

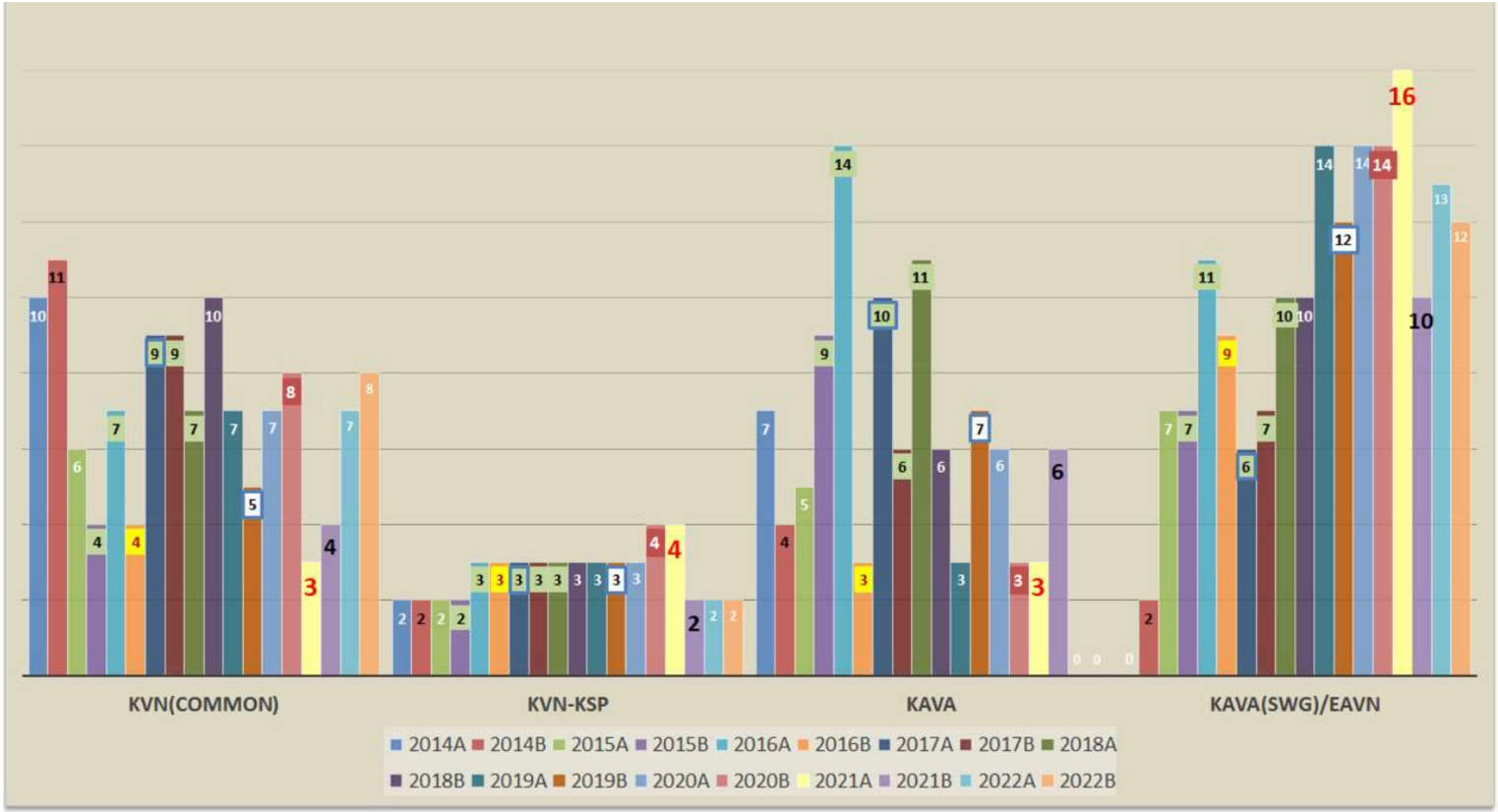




KVN & EAVN Operation Time



KVN & EAVN Proposal Status (Accepted)

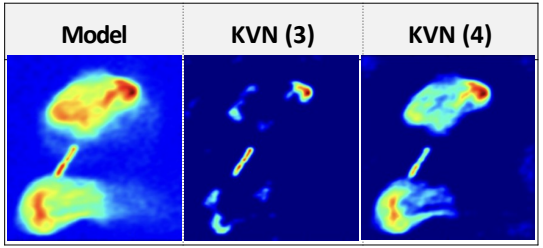


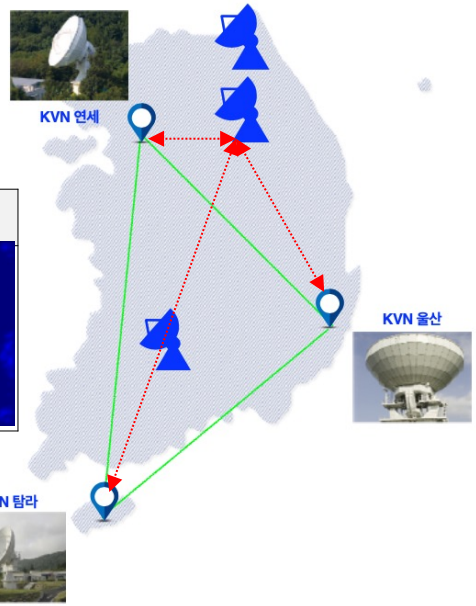

KVN 서울대평창전파천문대

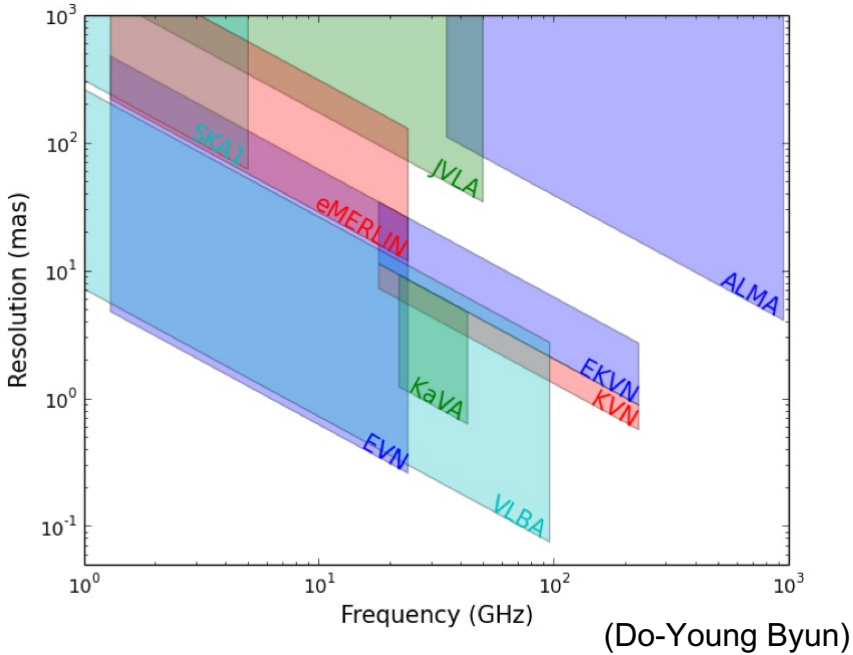

KVN SNU PyeongChang Radio Telescope

Extended Korean VLBI Network (EKVN)

- **Limitations of three KVN telescopes**
  - Imaging fidelity (poor UV-coverage)
  - amplitude calibration
  - only three pairs of VLBI measurements







(Do-Young Byun)

- 5 or more? Due to the budget limitation

- **4th KVN,** but working up to 1mm (230 GHz)
  - two baselines more → 6 baselines
  - better imaging (> 2 times)
  - amplitude self-calibration applicable
  - unique baselines in VLBI (100~500 km)

Extended Korean VLBI Network (EKVN)

- D = 21m shaped Cassegrain optics
  → same design with the KVN

- Aperture Efficiency
  – 60% @100GHz (current KVN ~50%)
  – 30% @230GHz (~15%)

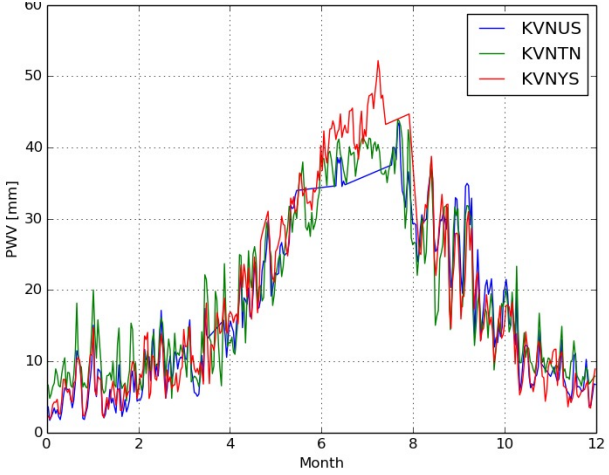
- Surface accuracy ≤ 100㎛ (~140)
  – main reflector panel ≤ 50㎛ (65)
  – sub reflector ≤ 20㎛ (50)
  – panel alignment ≤ 50㎛ (65)

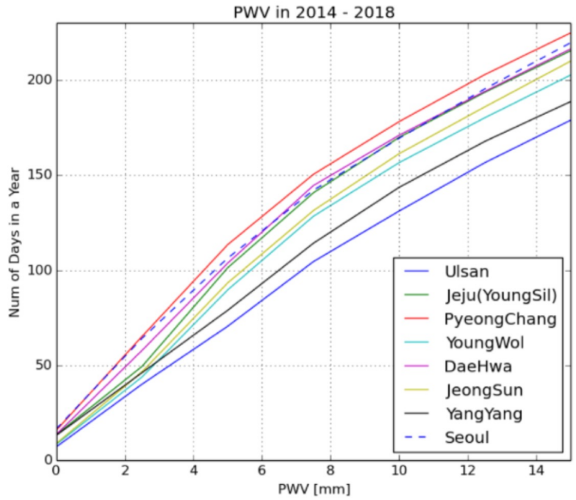
- Upgrade of BUS & panel supporters
  – to reduce deformation errors

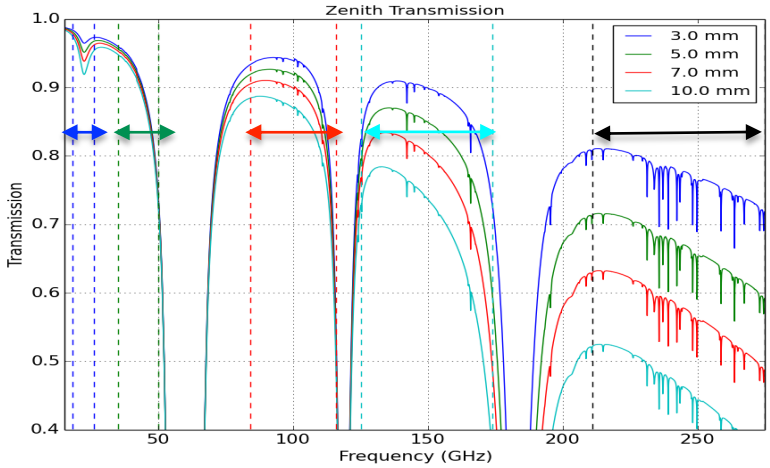
- Pointing accuracy < 3″

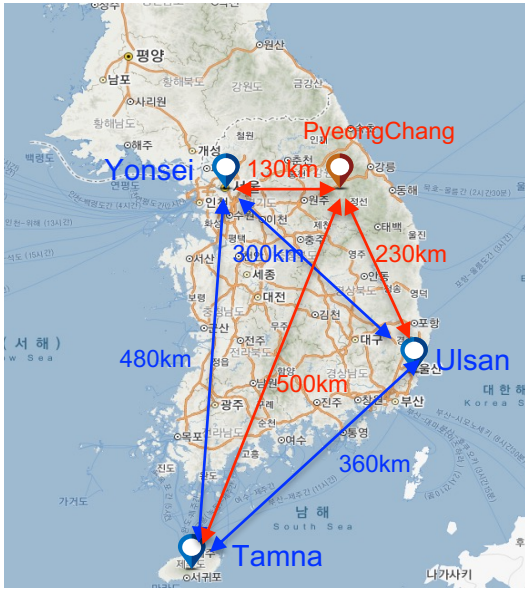


Atmospheric Conditions in Korea





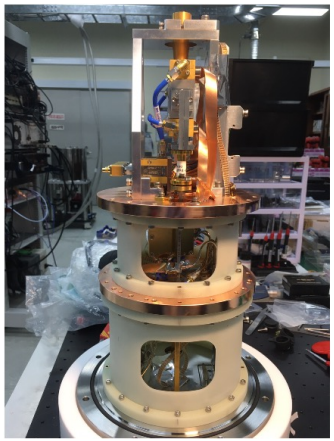


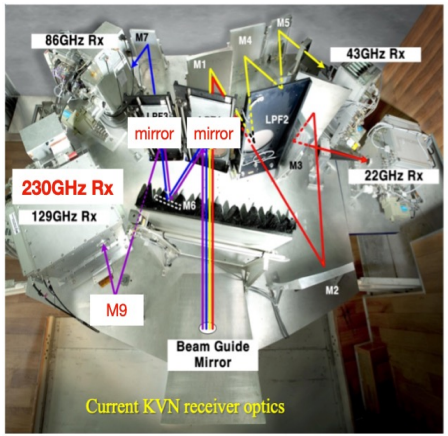


- Analyzed of 5-year weather data (2014-2018)
- SNU Pyeongchang site
  - transparency @ 230 GHz > 60% (< PWV 7 mm)
  - < PWV 7 mm ~110 days / year

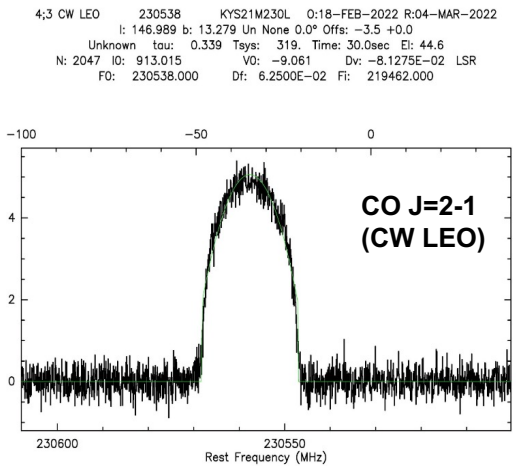
(Do-Young Byun)

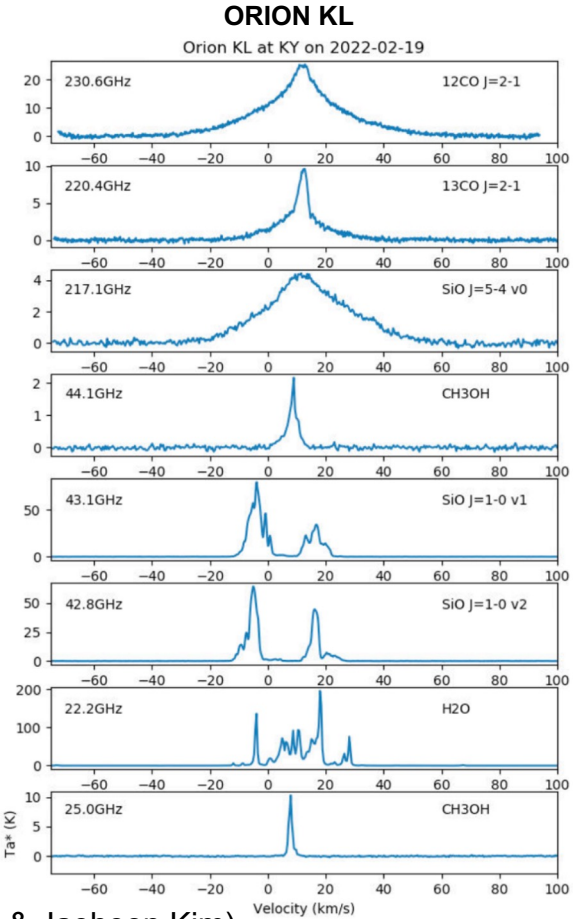
230GHz Test experiment with KVN Yonsei Telescope





(Jungwon Lee)



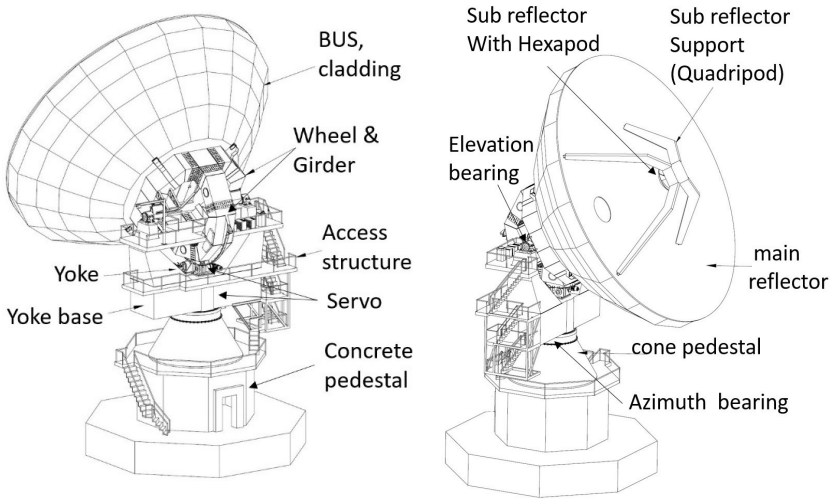


- KVN 230GHz Test experiment (~1 week, Feb 14~19, 2022)
  - Test receiver Trx ~ 70K @ 230 GHz
  - Backend: OCTAD + GPU spectrometer (128MHz x 16 IF)
  - HPBW: 12.1 / 14.3 arcsec @ AZ / EL
  - Measured aperture efficiency ~ 14% (EL~50 deg, Uranus)
  - Total surface accuracy ~ 130 μm (c.f. main dish ~ 90 μm)
  - Tsys ~ 200K, tau ~ 0.3, transmission ~ 74%, PWV ~ 3 mm

(Do-Young Byun & Jaeheon Kim)

EKVN: Antenna

a. Main reflector : Surface Panel, Surface Panel
b. Sub-reflector and positioner, quadripod
c. Backup-Structure (BUS) : diameter 21m with cladding, receiver room (5m x 5m x 2.5m)
d. Mechanical structure : Wheel & Girder, Cone pedestal, Yoke & Yoke base, Access,
e. AZ/EL Bearing, AZ/EL gear box, Encoder, AZ/EL Servo system, El Stow mechanism
f. Cable Wrap
g. Concrete pedestal
h. Electrical Equipment (grounding (2ohm), 3phase, single phase power)

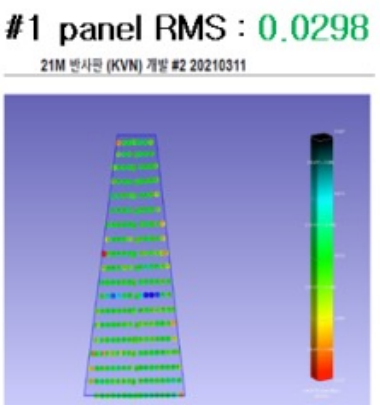


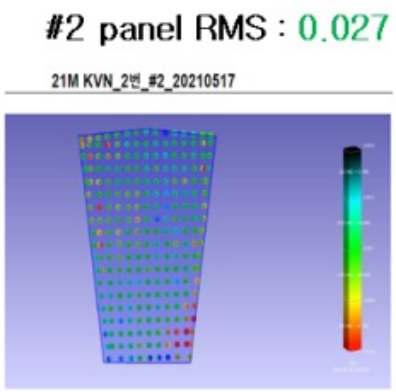
items	value
frequency [GHz]	**230**
λ [mm]	1.30
surface accuracy [**μm**]	**100μm**
surface efficiency (η_s)	0.40
blockage efficiency (η_b)	0.88
spillover efficiency (η_b)	0.95
illumination efficiency (η_l)	0.97
diffraction efficiency (η_d)	0.99
misc efficiency (η_m)	0.95
total efficiency ($\eta_t = \eta_b\eta_b\eta_l\eta_d\eta_m$)	0.76
Aperture efficiency ($\eta_a = \eta_s\eta_t$)	**30%**

Items	rms
Main Panel	60
Sub Reflector	30
Gravity	40
Wind	32
Thermal	20
Panel Alignment	50
Total RSS	**100μm**

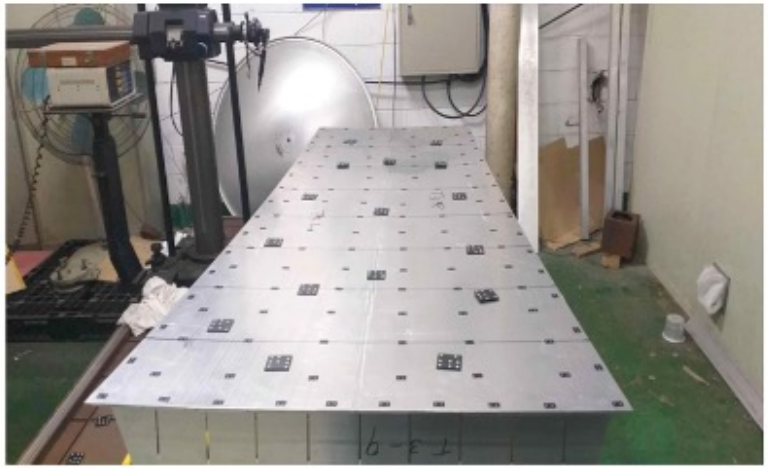
EKVN: Antenna

- Contract with the HighGain Antenna company (May 2021)
- TIM in Sep 2021
  - Mechanical, Servo
  - Test Observation Plan
- PDR in Nov, FDR in Dec 2021
- Prototype main-reflector panels
  - surface accuracy ~ 30-40 ㎛

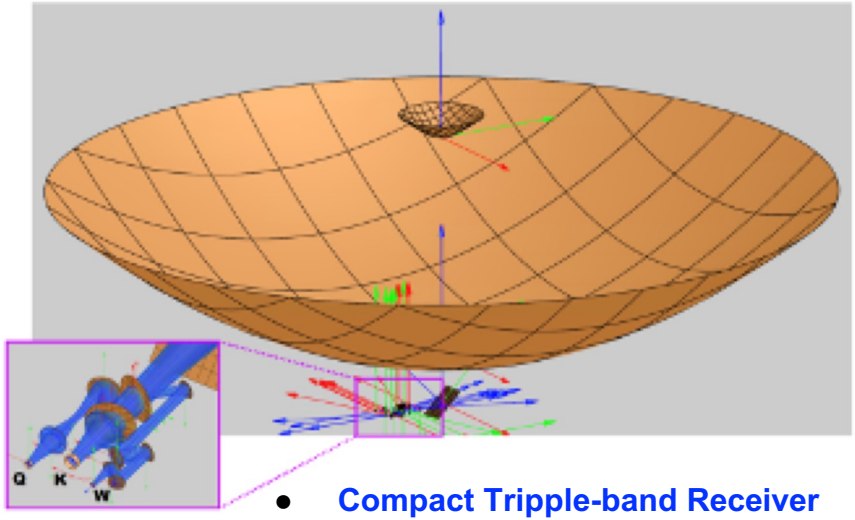


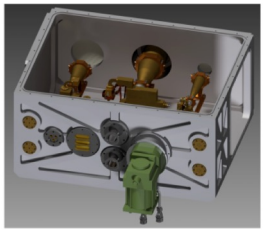






EKVN: 5-Channel (22/43/86/150/230 GHz) Receiver



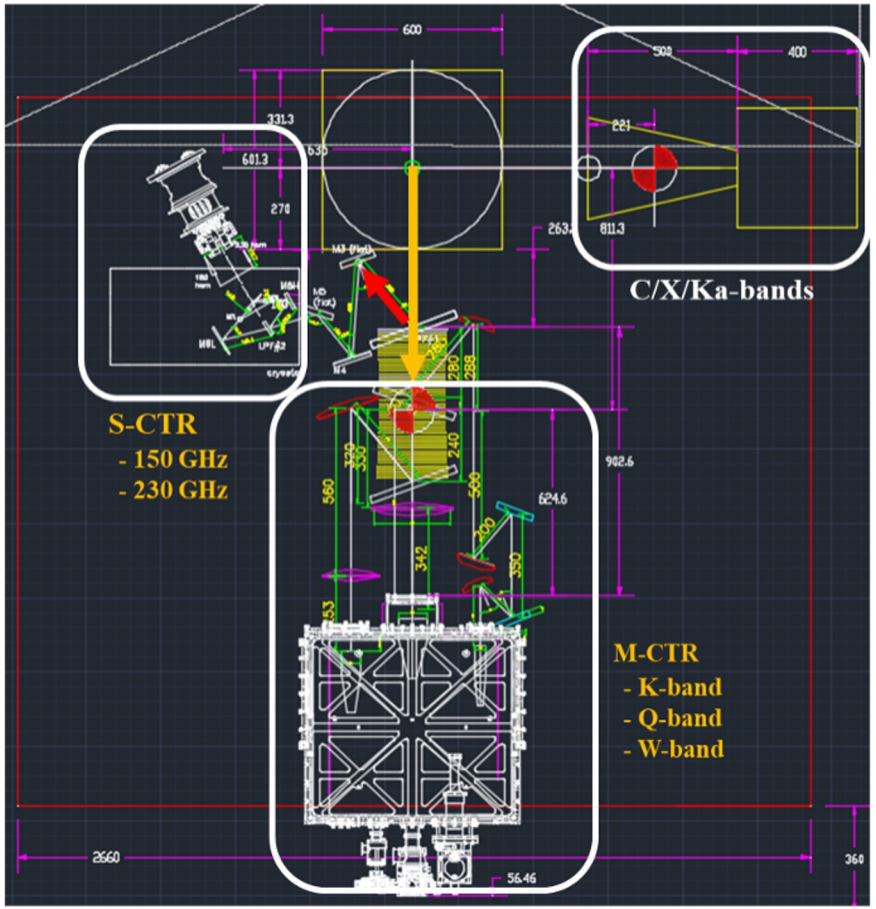


- **Compact Tripple-band Receiver**
  - K-band: 18-26 GHz
  - Q-band: 35-50 GHz
  - W-band: 85-116 GHz
- **150/230GHz SIS Mixer Receiver**
  - 127-182 GHz
  - 210-270 GHz

(Jihoon Choi)

- **C/X/Ka-band Receiver** (6-9 & 32 GHz)
- 45deg rotating mirror

E-KVN receiver configuration



Correlator & Network



Korea-Japan Correlation Center @ KASI

- HW correlator (up to 16 stations)
- EAVN correlator

Korea Research Environment Open NETwork

(dedicated science network

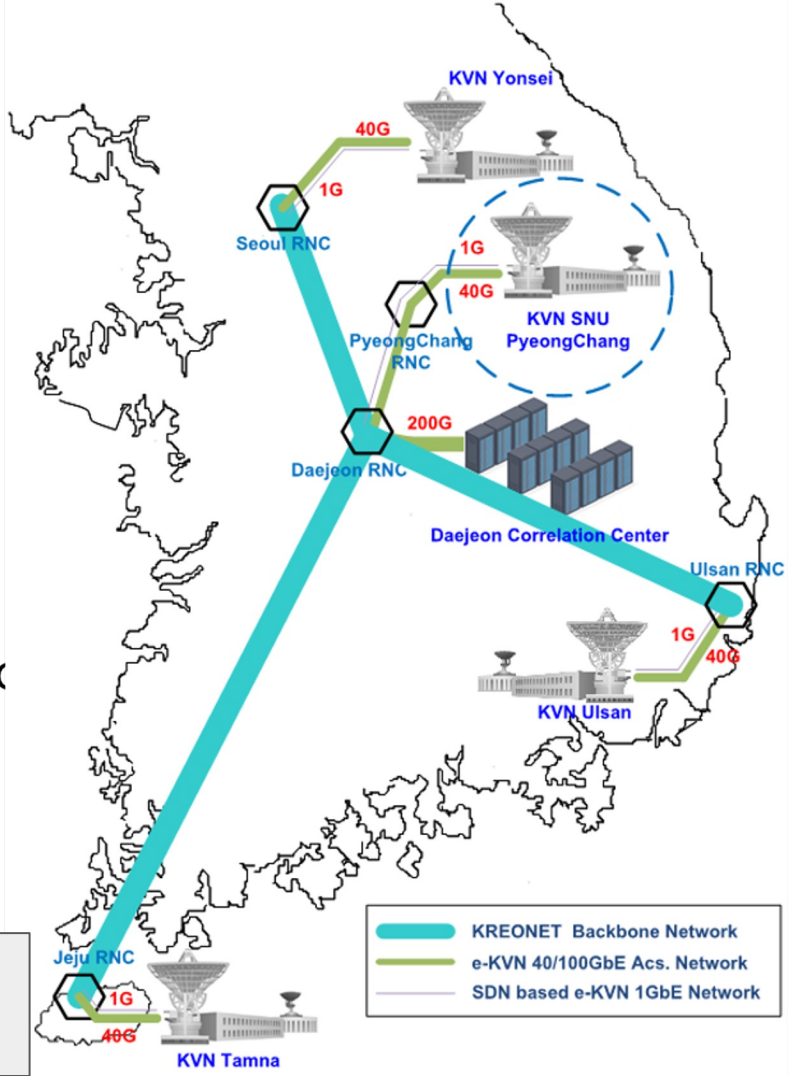


DiFX correlator

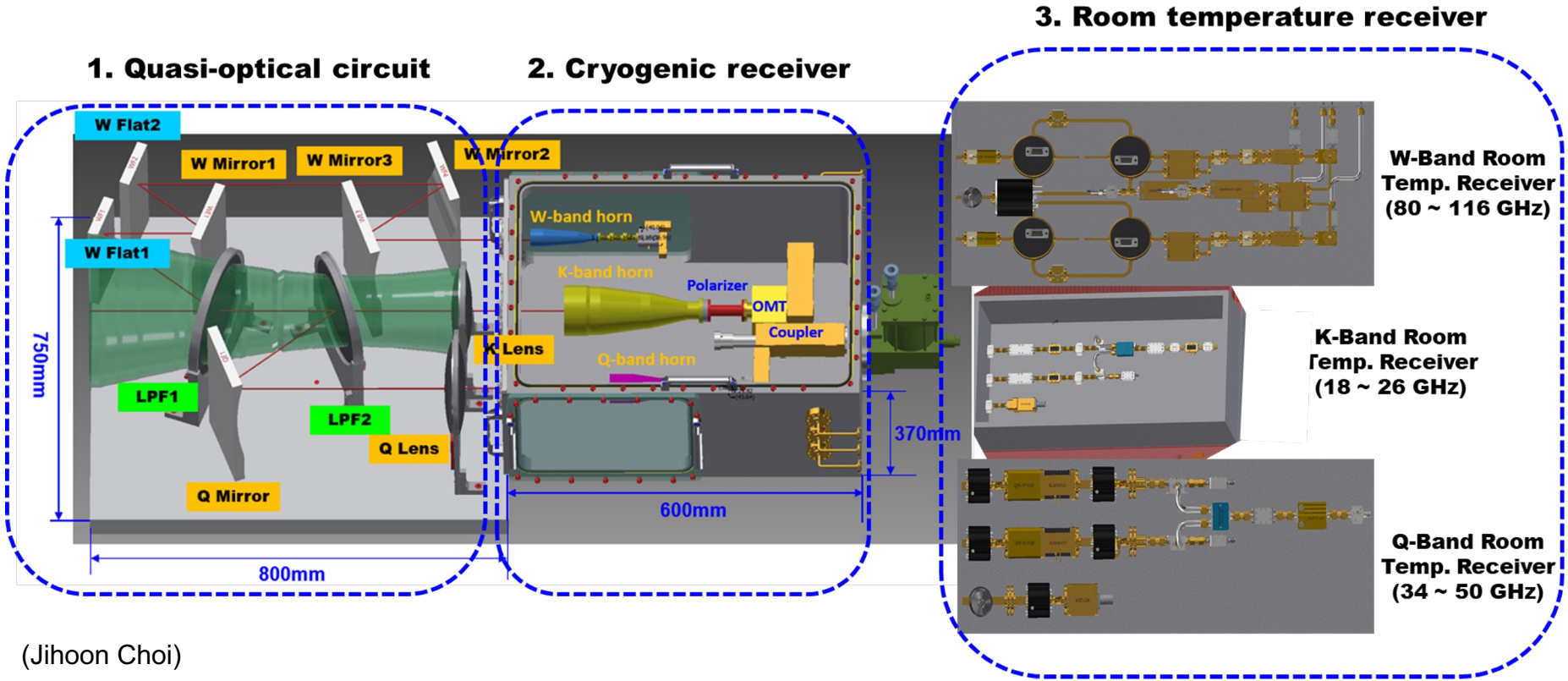
- KVN correlator
- Linux cluster
- 512 cores
- ~ 3PB

- KVN Sites : 10 – 40 (
- Daejeon : 100GbE
- Remote Operation
- e-Transfer & e-VLBI

- 400GbE upgrade @ KASI
- 40/100GbE connection to each KVN site



Compact Triple-band Receiver (CTR)



(Jihoon Choi)

EKVN: VLBI & SD Backend

- OCTAD x 2 EA
  - high-speed sampler and Digital BBC
  - 4 ADC of 16Gsps each
  - max. 32Gbps data rate
  - two OCTADs for 8 inputs (4band x 2pol)



- 4 ADC (4 x 16Gsps)
- Input Freq. 8 - 16GHz
- Digital Down Conversion
- Digital Filtering
- 4 x 10GbE output
- VDIF format

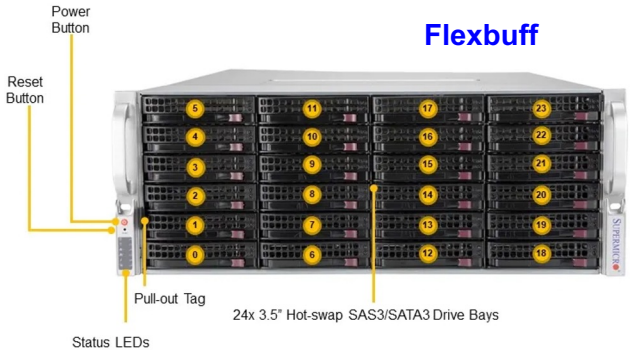
- Recorders
  - target recording rate : 64Gbps
  - Mark6 x 2 EA and Flexbuff x 1 EA



- Max 32 Gbps recording /w upgrade unit

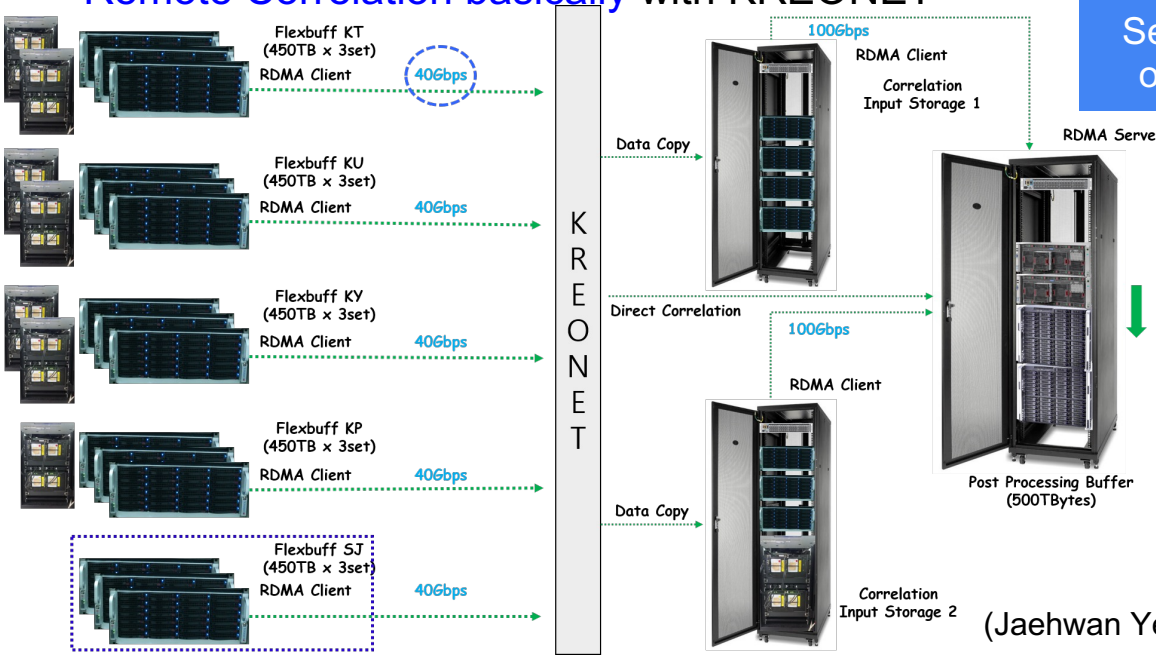
- Hydrogen maser (delayed)
- GPU Spectrometer



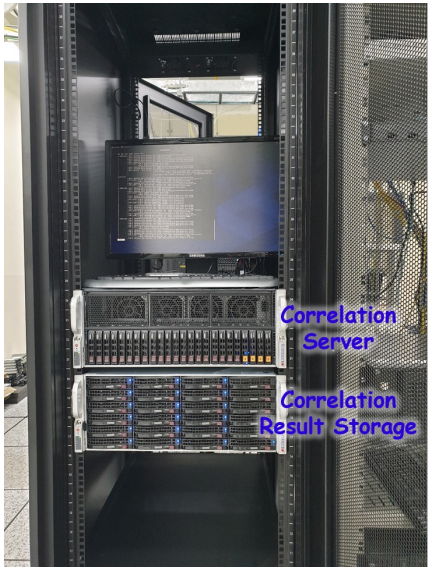


EKVN: New GPU SW Correlator

- **32Gbps R/L in real time mode**
- 64Gbps R/L in run time mode above 3 times for real observation time
- Maximum 5 stations (Tamna, Ulsan, Yonsei, Pyeongchang, Sejong)
  - future upgrade for EAVN
- GPU based and network based with RDMA (Remote DMA)
- Remote Correlation basically with KREONET



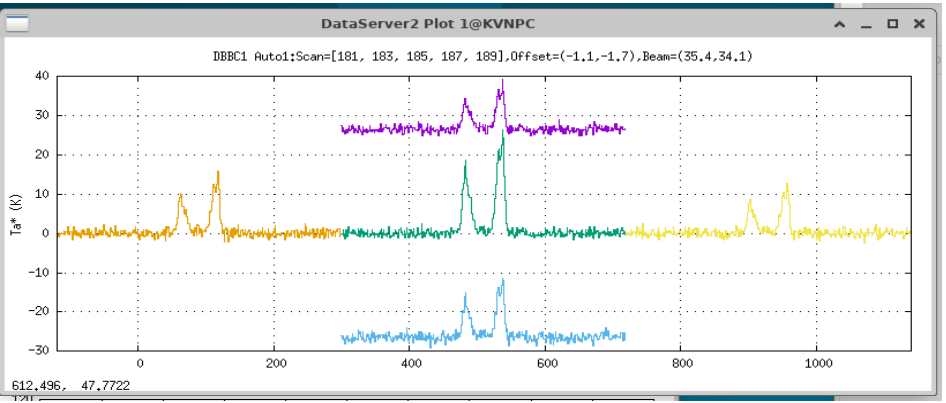
Se-Jin's Talk
on 30 Nov



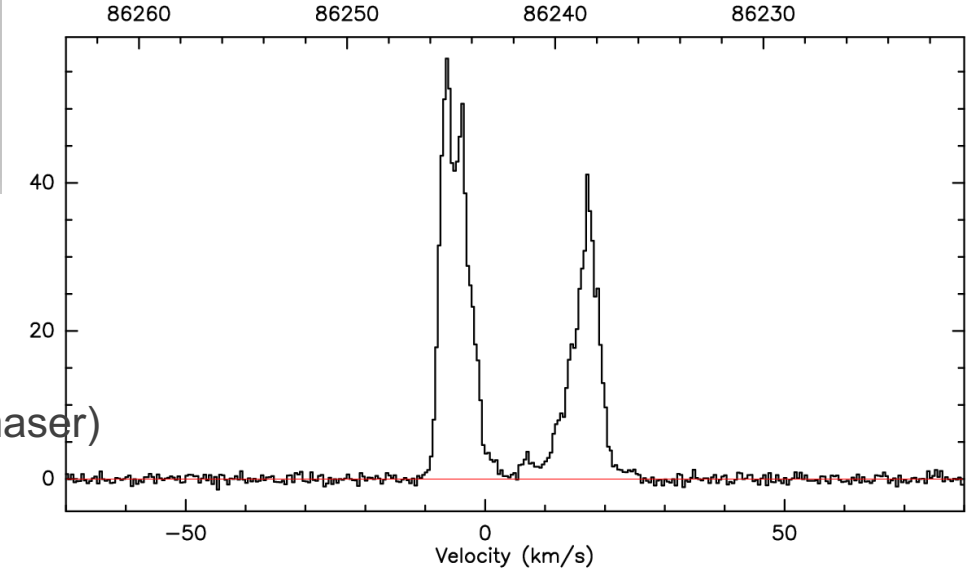
- GPU Card
  - 8 x Nvidia RTX3090
  - 10,496 Cuda Cores
  - 35.6 TFLOPS FP32
  - Final version: **RTX4090**
- Network Interface Card(NIC)
  - Support InfiniBand for RDMA (Remote DMA)
  - Mellanox 100G NIC

(Jaehwan Yeom)

EKVN: 100GHz First Light (21 Oct, 2023), ORION KL (SiO v=1, J=2-1)



193;1 ORION KL 86243 KPC21M86R 0:21−OCT−2023 R:21−OCT−2023
RA: 05:35:14.16 DEC: −05:22:30.6 Eq 2000.0 None 0.0° Offs: +0.0 +0.0
Unknown tau: 0.141 Tsys: 987. Time: 60.0sec El: 46.3
N: 1024 I0: 515.965 V0: 3.199 Dv: −0.4345 LSR
F0: 86242.4503 Df: 0.1250 Fi: 68557.5497



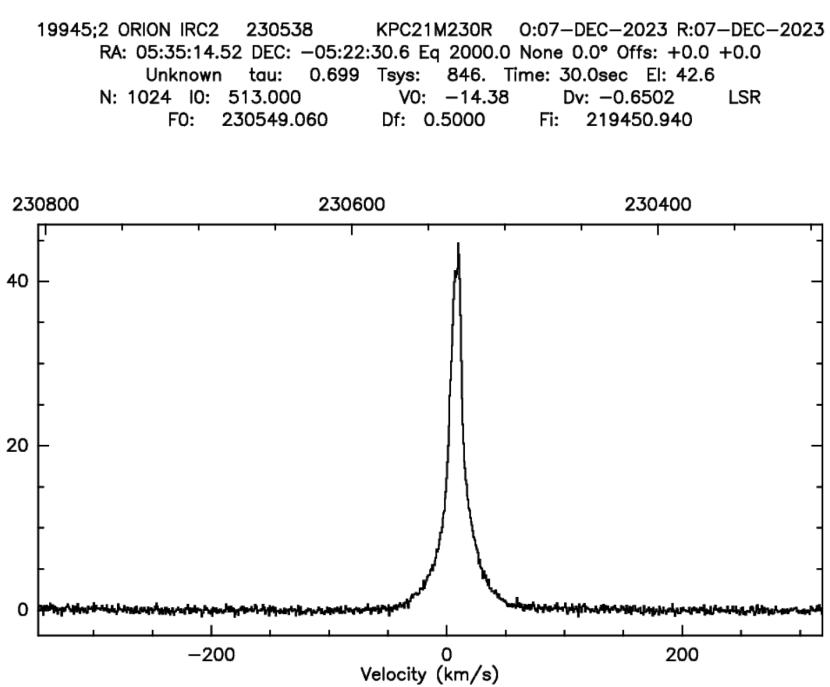
- ✓ Target: Orion KL
  (R.A. = 05:35 14.16, Dec. = -05:22:30.6)
- ✓ Rest frequency: 86.243 GHz (SiO v=1, J=2-1 maser)
- ✓ Manually modified pointing offset and focus

✓ **Date: Oct 22, 2023**

(Jaeheon Kim & Do-Young Byun)

EKVN: 230GHz First Light (7 Dec, 2023), ORION IRC2 (12CO 2-1)





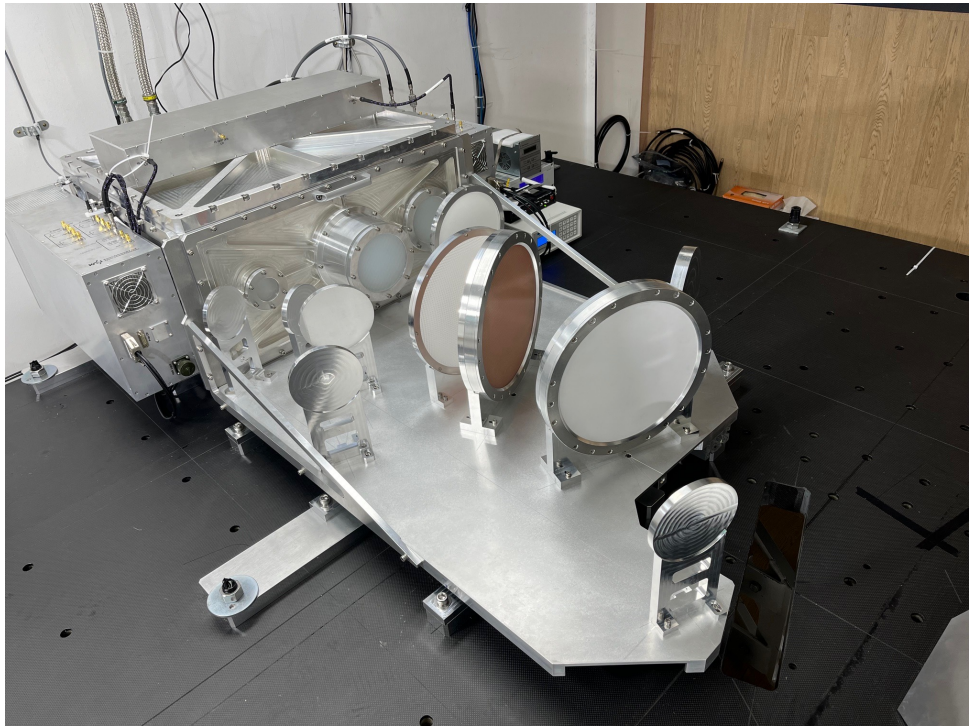
- ✓ Single Linear Pol & 2 Sideband
- ✓ Receiver Noise Temperature
  - ✓ LSB (< 222GHz) ~ 120K
  - ✓ USB (> 224GHz) ~ 120K
- ✓ IF 4 - 8GHz
- ✓ Backend : OCTAD + GPU Spectrometer , VFC (+Powermeter)

✓ **Date: Dec 7, 2023**

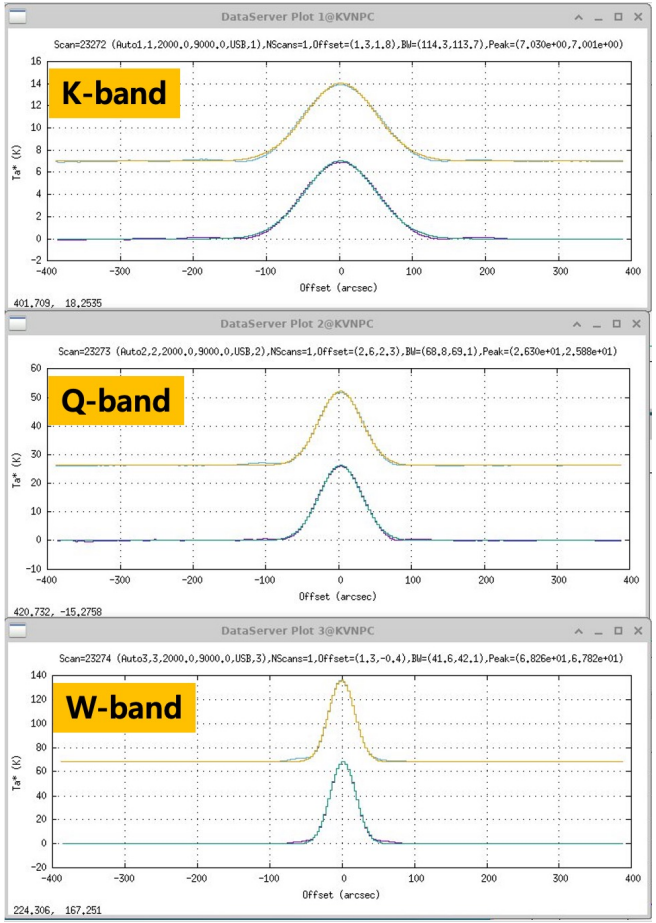
(Do-Young Byun)

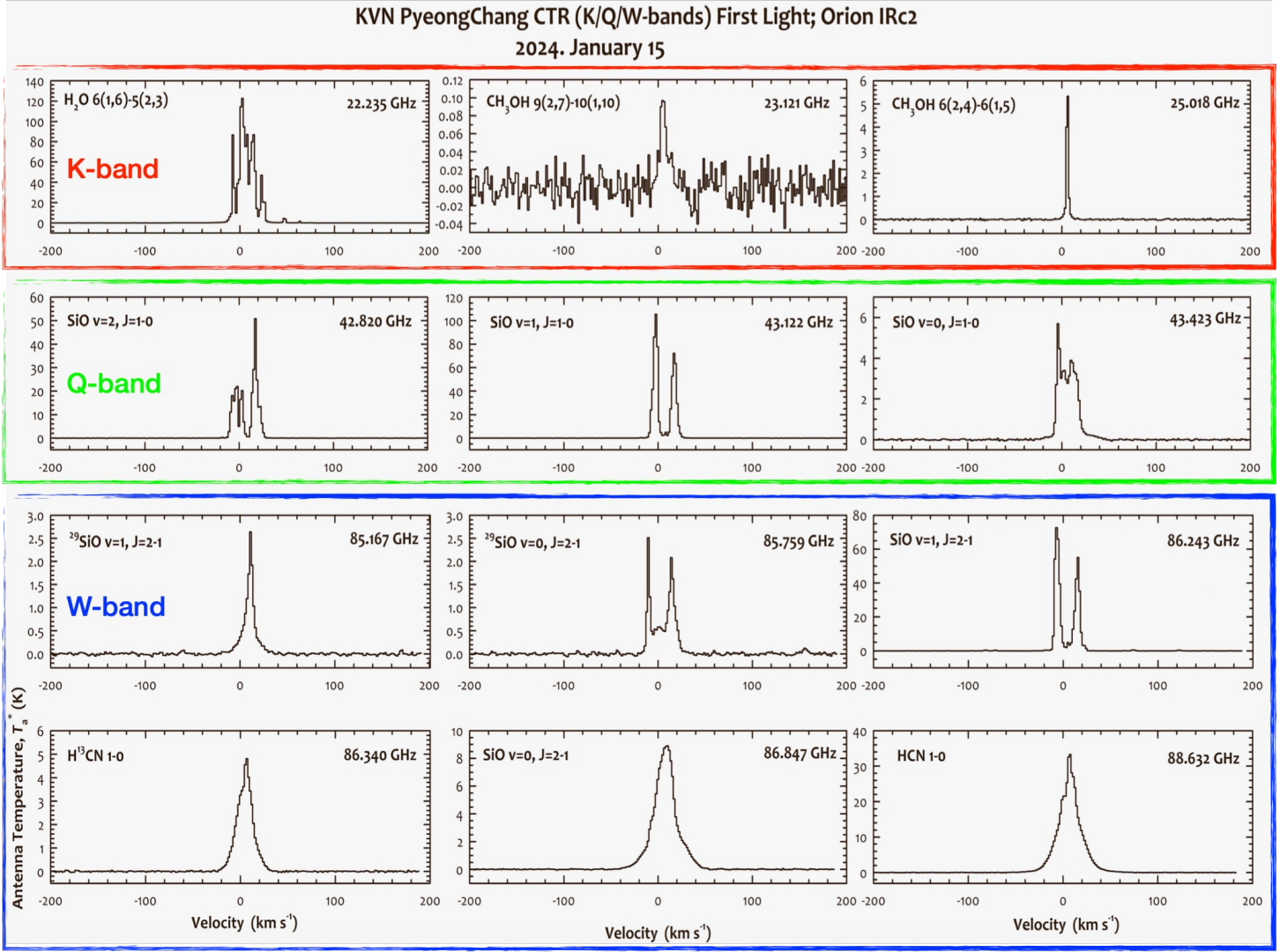
Compact Triple-band Receiver (CTR)

CTR installed at KPC



(Jihoon Choi)





- **Beam Alignment**

Freq. (GHz)	Az (arcsec)	El (arcsec)	Beam Size (arcsec)
25	0.0	2.4	118
43	1.4	2.7	69
90	–	–	33

- **Aperture Efficiency**

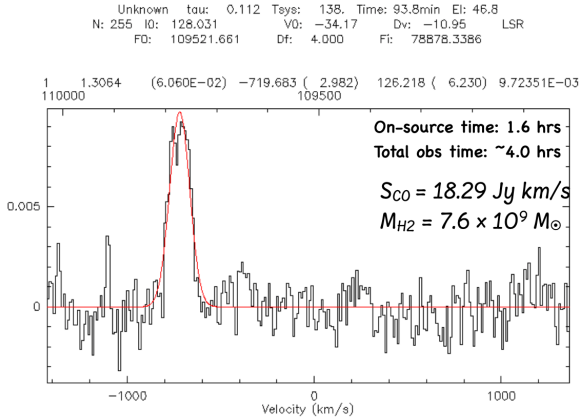
Freq. (GHz)	A.E. (%)
22	78
38	83
47	83
90	68

World Top Class Performance !!

KVN CO (1-0) survey for cluster galaxies

(Junhyun Baek)

- Thanks to the broadband capability of KVN, it is now allowed to
  the 115 GHz CO (1-0) line.
- In 2022B season, we carried out KVN single dish observations f
  (PI. Mina Pak) - the first scientific CO (1-0) obs for galaxies
- 6 galaxies with IFU data (3,000 km/s < radial vel. < 15,000 km/s)



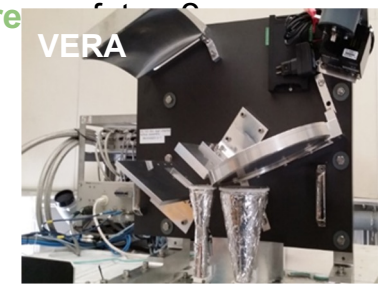


Simultaneous Multi-Freq. VLBI System in Globe

KVN (K/Q/W/D)
VERA (K/Q)
Sejong (K/Q/W)



Red: implemented or Tested
Orange: planned or under discussion
Gre



Yebes 40m (Spain, K/Q/W)



Nobeyama 45m (Japan, K/Q/W)



Metsahovi 14m (Finland, K/Q/W)

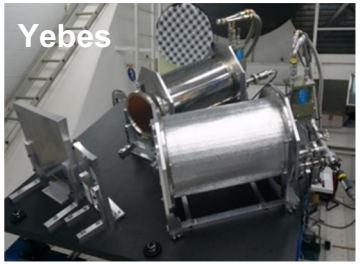


Tianma 65m (China, K/Q)



VLBA MK 25m (USA, K/Q/W) Future?





(K/Q/W/D+230GHz)

Common MF System for mm-VLBI in Globe

Sardenia 64m, Noto 32m, Medicina 32m (Italia, K/Q/W)



Mopra 22m (Australia, K/Q/W)

ATCA 22m x5 (Australia, Q/W)

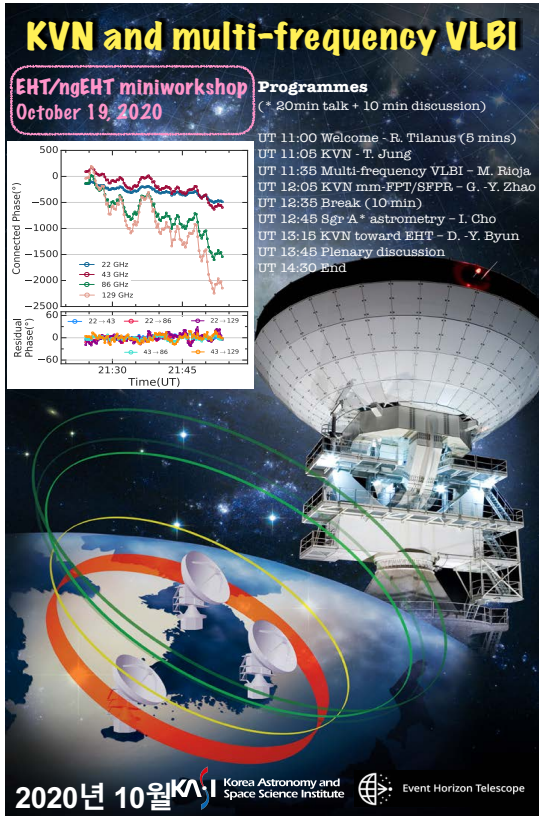


Multi-Frequency Mm-Wave Radio Telescopes
EU, ERATec workshop, Florence, Italy (Oct. 5-7)



Event Horizon Telescope & KVN

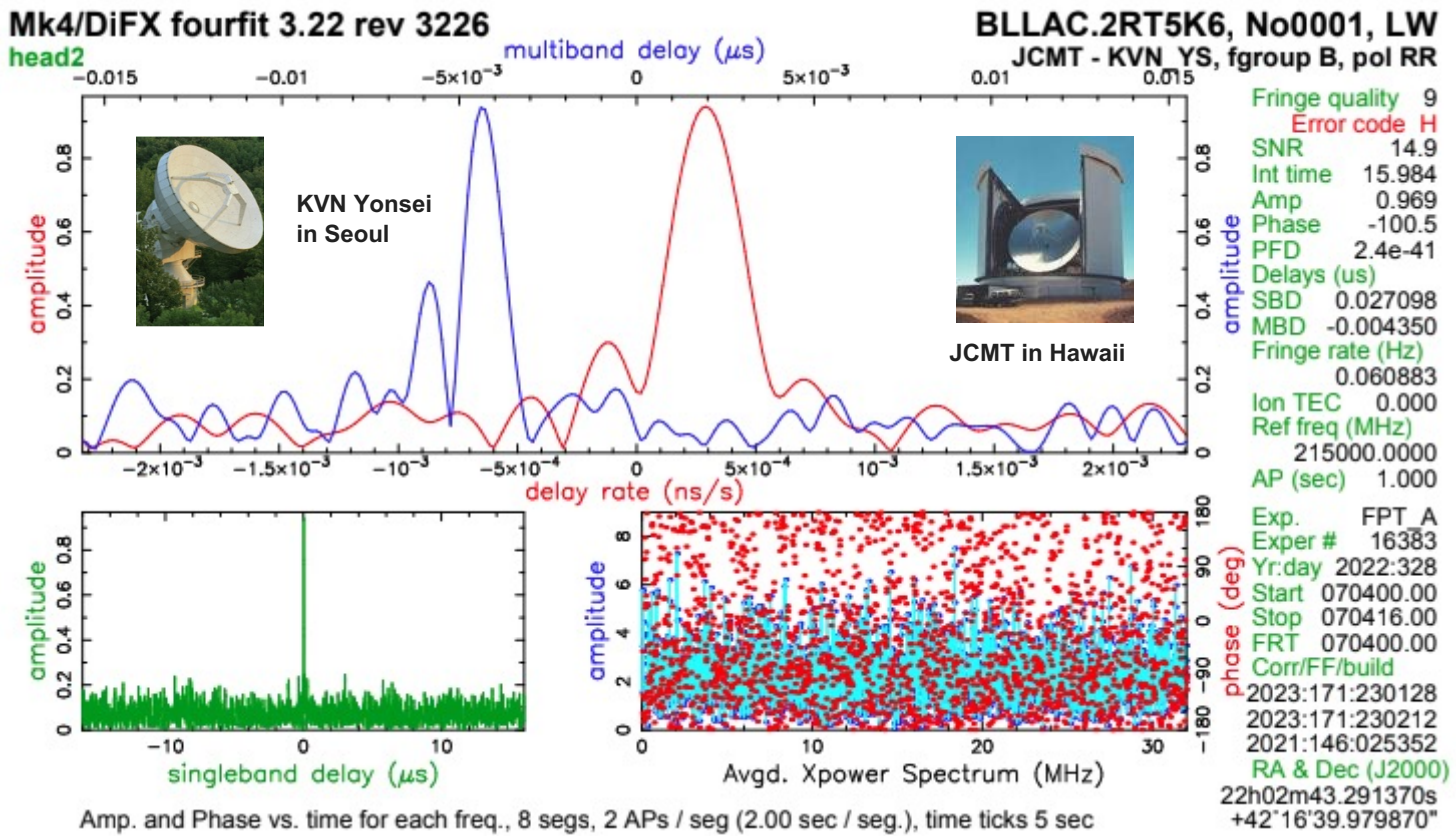
KVN's Simultaneous Multi-frequency System for the next generation Event Horizon Telescope







KVN Yonsei & PyeongChang Plans for 2024 EHT Campaign



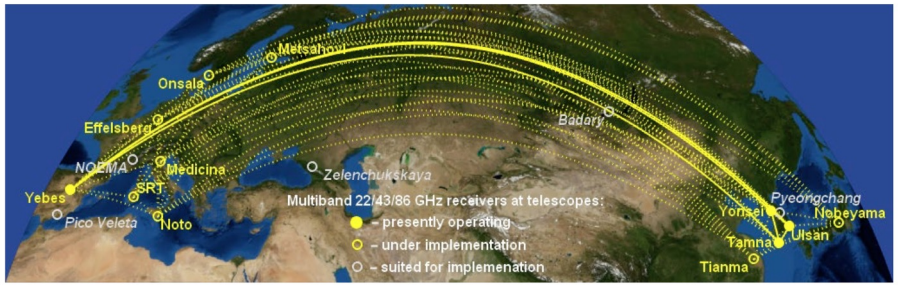
First 230 GHz Fringes between KVN Yonsei & JCMT (Nov. 2022)

Radio Astronomy with Multiband Receivers and Frequency Phase Transfer

RADIO ASTRONOMY WITH MULTIBAND RECEIVERS AND FREQUENCY PHASE TRANSFER:

Scientific Perspectives

Report from a Workshop held in Bonn on 12-14 October 2022



Richard Dodson[1], Cristina García-Miró[2], Marcello Giroletti[3], Taehyun Jung[4], Michael Lindqvist[5], Andrei Lobanov[6], Maria Rioja[7,1,2], Eduardo Ros[6], Tuomas Savolainen[8], Bong Won Sohn[4], Anton Zensus[6], Guang-Yao Zhao[9]

1 – ICRAR, Crawley, Australia; 2 – Yebes Observatory (IGN), Spain; 3 – IRA (INAF), Bologna, Italy; 4 – KASI, Daejeon, Korea; 5 – Onsala Space Observatory, Sweden; 6 – MPIfR, Bonn, Germany; 7 – CSIRO, Bentley, Australia; 8 – Aalto University, Espoo, Finland; 9 – IAA, Granada, Spain.

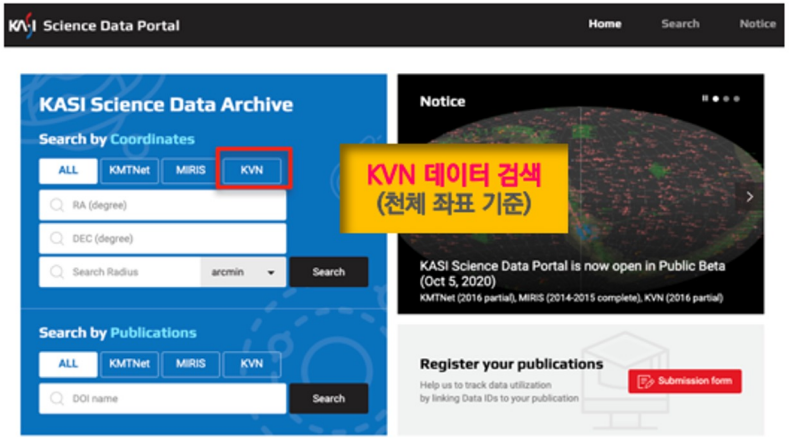
Table 1. Status of existing, planned, and potential future multiband SOP receivers

Antenna	Receiver Band				
	22 GHz	43 GHz	86 GHz	129 GHz	230 GHz
KVN: Yonsei	in operation	in operation	in operation	in operation	*planned*
KVN: Ulsan	in operation	in operation	in operation	in operation	
KVN: Tamna	in operation	in operation	in operation	in operation	
KVN: Pyeongchang	*in 2024/Q3*	*in 2024/Q3*	*in 2024/Q3*	*in 2024/Q3*	*in 2024/Q3*
Sejong	in operation	in operation	*possible*		
Yebes	in operation	in operation	in operation		
ATCA *	in operation	in operation	in operation		
Noto	*in 2023/Q4*	*in 2023/Q4*	*in 2023/Q4*		
SRT	*in 2023/Q4*	*in 2023/Q4*	*in 2023/Q4*		
Medicina	*in 2024/Q2*	*in 2024/Q2*	*in 2024/Q2*		
Effelsberg	*in 2024/Q2*	*in 2024/Q2*	*in 2024/Q2*		
Metsähovi	*In 2026/Q1*	*In 2026/Q1*	*In 2026/Q1*		
Onsala	*design*	*design*	*design*		
Tianma	*planned*	*planned*	*planned*		
Nobeyama	*under tests*	*under tests*	*under tests*		
Mopra	*planned*	*planned*	*planned*		
Pico Veleta	*possible*	*possible*	*under tests*	*possible*	*under tests*
NOEMA	*possible*	*possible*	*possible*	*possible*	*possible*
APEX	*possible*	*possible*	*possible*	*possible*	*possible*
Zelenchukskaya	*possible*	*possible*	*possible*		
Badary	*possible*	*possible*	*possible*		

* - limited frequency range, operating in the paired-antenna mode, using single-band receivers.

다운로드:https://drive.google.com/file/d/1jeu2hSy77EX_9Vf5L8LQ-goi6vWa7vyi/view?usp=drive_link

KVN에서 생산된 연구데이터 관리와 공유·활용을 통한 융합연구 및 오픈사이언스 선도



- KVN 홈페이지 : http://kvn.kasi.re.kr
- EAVN 홈페이지: http://eavn.kasi.re.kr
- KASI Science Data Portal : http://data.kasi.re.kr

- 2012년 이후 모든 KVN 관측데이터 아카이브 DB 구축
- 웹기반 관측운영 효율화 & 사용자 지원
- 관측 자료처리 파이프라인 개발
- DB 활용한 다파장/후속 연구성과 창출기반 구축

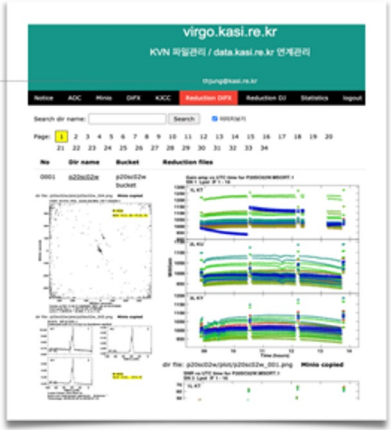




연구데이터 공개현황

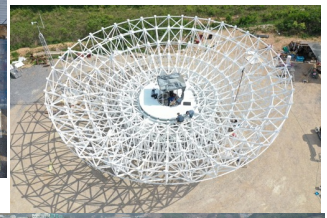
- KVN & EAVN 모든 데이터 공개
- 관측 데이터 배포 후, 18개월 독점사용 기간 후 모두 공개 원칙

Data Management Project



EKVN: Upcoming Schedules

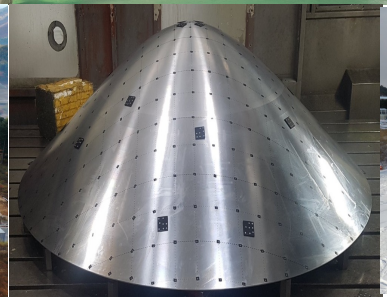
- (Feb) CTR test observations & Fringe Test
- (Mar) VLBI test (CTR + 230GHz)
- (Apr) EHT 2024 campaign
- (May) KVN SNU PyeongChang Opening Ceremony
- (Sep~) KVN/EAVN 2024B (shared-risk, both for single dish & VLBI)
- EKVN Science Workshop for Single Dish (15 Feb, 2024)
    - More KVN science events for SD & VLBI !!













Nanshan 26 m
KASI/DHC
Miyun 50 m
Sejong 22 m
Yonsei 21 m
Ulsan 21 m
Gifu 11 m
Usuda 64 m
NAOJ/OCTACOR2
Mizusawa 20 m
Tamna 21 m
Takahagi 32 m
FAST 500 m
Hitachi 32 m
Kunming 40 m
TNRT 40 m
Tianma 65 m
Sheshan 25 m
SHAO/DBFX
Ishigakijima 20 m
Iriki 20 m
Yamaguchi 32 m
Ogasawara 20 m
Nobeyama 45 m
Thank you !
The East Asian VLBI Network
(Image Credit of the ground photograph: Reto Stöckli, NASA Earth Observatory)
6.7 GHz
8 GHz
22 GHz
43 GHz