# Development of Software Digital Filter based on GPU for East-Asian VLBI Network

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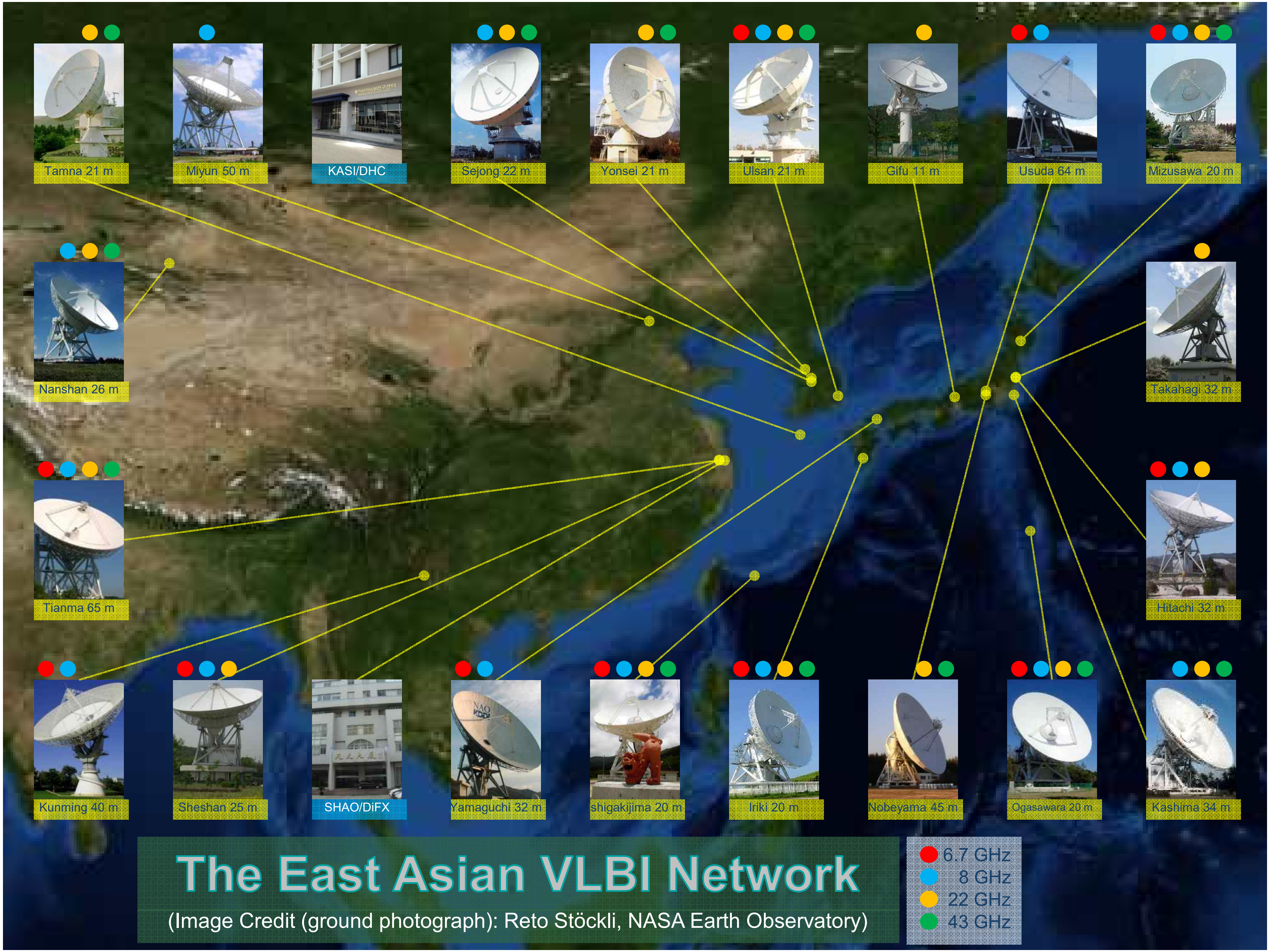



# The East Asian VLBI Network

(Image Credit (ground photograph): Reto Stöckli, NASA Earth Observatory)

# EAVN: Specifications (as of 2018 Sep 6)

- Number of (potential) telescopes: 20 (17 telescopes have participated in previous EAVN observations one or more times)
  - Korea: 4, China: 5, Japan: 11
- (Possible) frequency coverage:
  - 6.7 GHz (11 stations), 8 GHz (15), 22 GHz (16), 43 GHz (12)
- (Expected) angular resolution:
  - 2.4 mas (6.7 GHz; Ogasawara – Kunming)
  - 1.5 mas (8 GHz; Ogasawara – Nanshan)
  - 0.6 mas (22 GHz; Ogasawara – Nanshan)
  - 0.3 mas (43 GHz; Ogasawara – Nanshan)
- Sensitivity for 7-$\sigma$ fringe detection ($\tau$ = 60 s, $B$ = 256 MHz):
  - 1.6 mJy (8 GHz; Tianma – KVN)
  - 9.5 mJy (22 GHz; Tianma – KVN)
- (Expected) recording rate: $\geqq$ 1 Gbps (= 256 MHz BW)
- (Currently-used) correlator:
  - KASI (Korea): Daejeon Hardware Correlator (DHC) and DiFX
  - SHAO (China): DiFX

# Recent Updates (in recent one year)

- Launch of EAVN open-use operation
- System change/upgrade
  - Kunming 40 m: 6.7 GHz receiver available
  - Nanshan 26 m: 43 GHz cooled receiver under testing
  - Yamaguchi 32 m: Shut-down of operation at 22 GHz
  - Nobeyama 45 m: New quasi-optics at 22/43/(86) GHz simultaneous reception (HINOTORI Project led by Imai-san)
  - VERA:
    - Dual polarization system: receiver development ongoing
    - Installation of 22/43 GHz simultaneous reception system at all stations
  - 2 Gbps operation
    - KVN: operational (up to 16 Gbps)
    - JVN, VERA: test observations ongoing
- EAVN AGN Campaign in 2018

# EAVN (+ Italy) AGN Campaign in 2018

- Main purpose
  - To obtain scientific results with EAVN
  - To conduct VLBI monitoring quasi-simultaneously with EHT + ALMA campaign
  - (To evaluate system performance of EAVN)
  - (To check up on the array operation and availability of KEY/VEX files at each station)
- Brief summary of the Campaign
  - Main target: Sgr A* (43 GHz), M87 (22 and 43 GHz)
  - Total observing time: 186 hours/18 epochs (83 hours/9 epochs at 22 GHz; 103 hours/12 epochs at 43 GHz)
    - cf. EAVN campaign in 2017: 40 hours/5 epochs at 22 GHz; 100 hours/12 epochs at 43 GHz
  - Number of participating telescopes: 14 (Italy: 2, China: 2, Korea: 3, Japan: 7)

Correlation and data reduction ongoing

# Short- and Mid-Term Agenda

| Year | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|
| Actions | ･Imaging tests<br>･Science commissioning observations at 22/43 GHz<br>･Fringe tests at 6.7 GHz<br>･Launch of EAVN Science WG | ･Performance evaluation and science commissioning at 6.7/22/43 GHz<br>･Practice of the array operation (scheduling, telescope operation, data handling, etc.) | ･(Late 2018) Risk-shared open use at 22/43 GHz<br>･Performance evaluation at 6.7 GHz<br>･Performance evaluation of 2 Gbps mode | ･(Late 2019) Risk-shared open use at 6.7 GHz<br>･(Late 2019 or early 2020) Risk-shared open use of 2 Gbps mode<br>･Performance evaluation for extending observation modes (8 GHz, 2-pol., etc.) | ･(Late 2020) Risk-shared open use of dual-polarization mode<br>･Test observation at low frequencies (< 5 GHz) |
| Freq. | 6.7/22/43 GHz | 6.7/22/43 GHz | 6.7/22/43 GHz | 6.7/8/22/43 GHz | (1.6/2/5/)6.7/8/22/43 GHz |
| Purposes | ･Evaluation of array performance and array operation commissioning<br>･Performance evaluation at 6.7/22/43 GHz | ･Initial scientific outputs from EAVN<br>･Confirmation of performance at all frequencies | ･Launch of regular operation of EAVN<br>･Conformation of performance for wideband observation | ･Stable operation of EAVN<br>･Confirmation of performance for various observation modes | ･Regular operation with various observation modes<br>･Investigation of low-frequency VLBI with FAST and other telescopes |

# Short-Term Agenda

- Fringe tests and confirmation of imaging capability
  - 6.7 GHz with JVN and CVN (Tianma, Kunming)
  - With the data rate of 2 Gbps
  - With Nanshan at 43 GHz
- Dual-polarization capability
- Dual- (triple-)band simultaneous receiving system
  - KVN: operational
  - VERA: temporary installation, VLBI test ongoing
  - Nobeyama 45 m: HINOTORI Project (22/43/86 GHz receiving system: system development ongoing led by Imai-san)

# Mid- and Long-Term Agenda

- Collaboration with the Australian LBA
- Capability of low-frequency (< 5 GHz) observations (as a 'pathfinder' of SKA)
  - Installation of VLBI backend system at FAST → opportunity of a VLBI test observation at L-band in 2020 and beyond
  - Future plan of VLBI observations with EVN
  - VLBI observation at 1.6/2 GHz (there are at least 4 telescopes which are available at below 5 GHz except FAST)
  - Possibility of installation of 6.7(/8) GHz receivers in FAST? (is it possible to install equipment with external budgets?)
- Collaboration with the Thai VLBI Network (TVN)
  - Available from 2020 or later?

# Why SW Digital Filter?

- Each station located in Japanese VLBI Network (JVN), there are no HW DFB at station, so the observation data was recorded with wideband (over 512 MHz BW).
- In order to make a correlation with other stations, digital filtering work is needed, and recently the HW DFB is being used to be filtered, but it took quite long time for filtering of observation data.
- So SW digital filter at KJCC is needed to support and reducing the time for filtering work.

# Digital Filter

- Key point : Convolution

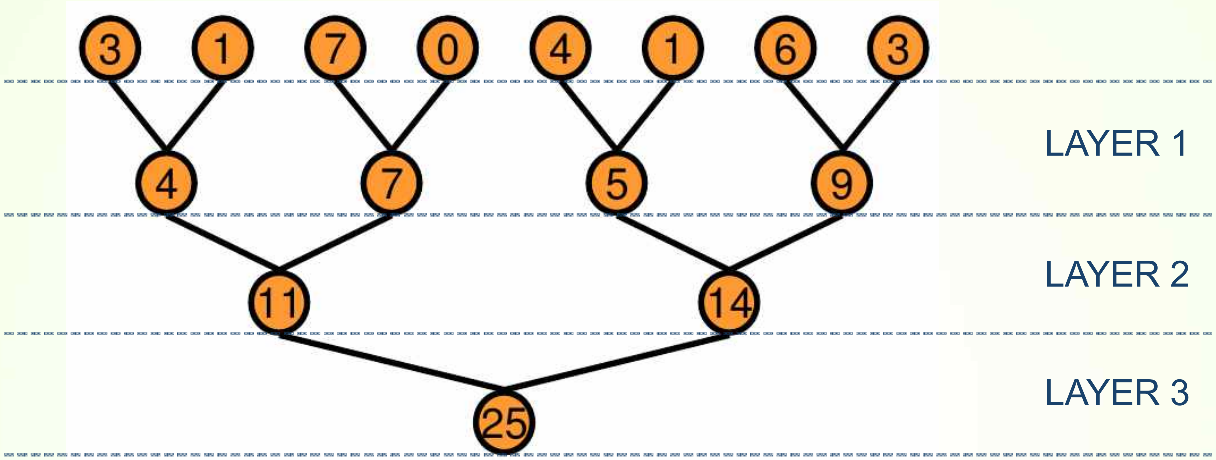
$$y(n) = \sum_{k=0}^{M} h(k)x(n-k) = \sum_{k=0}^{M} x(k)h(n-k)$$

- *h* is filter coefficient, *x* is input data
- Range k=0 to M, combination of Multiply and Add operation

➔ Important thing of digital filter is precise operation like resolution, but it needs to reduce the operation time for huge observation data to be processed within real-time.

# Filter Design using GPU

- ADD Operation, k=0 to M




- How can reduce time of the ADD operations?
  - If M=7, (8 x MULTIPLY) and (7 x ADD), **3 LAYER**

- The minimum unit of GPU operation is thread. So we have to perform synchronization between thread in every layer, and we could only approach the indicated memory address.
- It is quit complicated operation.
- So the add operation should be reduced to have high performance.

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# Parallel Reduction

- **<u>If the LAYER is increased, it needs much more time rather than operation rate</u>**
- **Refer to Nvidia paper : table**
- **Experiments**
  - G80 GPU used
  - 900MHz DDR
  - Support 86.4GB/s B.W.
  - Support 345.6GFLOPS
  - Experiment conditions : only conducting the add operation for the 4M sample(2^22). Only add operation is conducted and it needs the 15.7GFLOPS operation for 1 sec input data.
  - For this, we can see the operation indicated in table, the operation time is more needed for the required operational rate.
  - 22 layers are needed for 4M sample input. The input and output data rate is influenced to operation time, but it needs much more time by the number of layer.

| | Time ($2^{22}$ ints) | Bandwidth | Step Speedup | Cumulative Speedup |
|---|---|---|---|---|
| **Kernel 1:** interleaved addressing with divergent branching | 8.054 ms | 2.083 GB/s | | |
| **Kernel 2:** interleaved addressing with bank conflicts | 3.456 ms | 4.854 GB/s | 2.33x | 2.33x |
| **Kernel 3:** sequential addressing | 1.722 ms | 9.741 GB/s | 2.01x | 4.68x |
| **Kernel 4:** first add during global load | 0.965 ms | 17.377 GB/s | 1.78x | 8.34x |
| **Kernel 5:** unroll last warp | 0.536 ms | 31.289 GB/s | 1.8x | 15.01x |
| **Kernel 6:** completely unrolled | 0.381 ms | 43.996 GB/s | 1.41x | 21.16x |
| **Kernel 7:** multiple elements per thread | 0.268 ms | 62.671 GB/s | 1.42x | 30.04x |

# Required items

- **EAVN Filter Specification**
  - 2Gbps (512 MHz BW) → 1Gbps(256 MHz BW)/16channel
  - FP32 (single-precision 32bit) operation is needed
  - In GPU, FP16 is supported
  - But, coefficient loss in FP16 is occurred
    - Due to 2^-14 ~ 2^15 (0.00006103 ~ 32,768) precision
    - It is not able to adopt FP16 | s | e | x | p | | | . | m | a | n | t | i | s | s | a | | |
  - EAVN DF : 511 coefficients are used
    - For this, 1,047,552,000,000 FLOPS = 1TFLOPS operations are needed
    - 9 LAYERS operation are also needed
  - When data reading from server, data should be aligned and after filtered with GPU, the output data for Mark5B or VDIF is formed with re-quantization, then saved to the storage.
  - Data Input & Output should be considered.

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# GPU board selection

- In order to satisfy the requirement of EAVN DF,
- It should be supported with minimum 10TFLOPS in FP32 and with over 100 GB/s memory BW


- The Titan V and Xp specification are summarized in this table.
- Titan Xp is a bit good performance compared to the price, but we selected Titan V board to use the Tensor Core which is recently supported.

| | Titan V | Titan Xp |
|---|---|---|
| CUDA Cores | 5120 | 3840 |
| Tensor Cores | 640 | N/A |
| ROPs | 96 | 96 |
| Core Clock | 1200MHz | 1485MHz |
| Boost Clock | 1455MHz | 1582MHz |
| Memory Clock | 1.7Gbps HBM2 | 11.4Gbps GDDR5X |
| Memory Bus Width | 3072-bit | 384-bit |
| Memory Bandwidth | 653GB/sec | 547GB/sec |
| VRAM | 12GB | 12GB |
| L2 Cache | 4.5MB | 3MB |
| Single Precision | 13.8 TFLOPS | 12.1 TFLOPS |
| Double Precision | 6.9 TFLOPS (1/2 rate) | 0.38 TFLOPS (1/32 rate) |
| Half Precision | 27.6 TFLOPS (2x rate) | 0.19 TFLOPs (1/64 rate) |
| Integer (INT8) | 55.2 TOPS (4x rate) | 48.4 TOPS (4x rate) |
| Tensor Performance (Deep Learning) | 110 TFLOPS | N/A |
| Other Native INT Operations | INT32, DP4A, DP2A | DP4A, DP2A |
| GPU | GV100 (815mm2) | GP102 (471mm2) |

# EAVN Digital Filter System

- **Supermicro 4029GP TRT**
  - Intel XEON Gold 6154 2ea
  - 384GBytes DDR4
  - SAS RAID card 2ea : 256 TB HDDs capacity
  - 10Gb SFP+ Ethernet

Front

Rear

# Filtering using Titan V(Tensor Core GPU)

- 2Gbps (512MHz BW, 1channel) → 1Gbps(256MHz BW, 16channel)
- Original data : 95 sec
- Filtering time : Takes 106 sec
- 1.1 times

using 1 GPU card

- If 2 GPU board will be used, the filtering will be processed with real-time.

oper@localhost:~/work/kavafilter/eavnconverge_v2.3

File Edit View Search Terminal Help

```
------ Shared Memory Segments --------
key        shmid      owner      perms      bytes      nattch     status

------ Semaphore Arrays --------
key        semid      owner      perms      nsems

[oper@localhost eavnconverge_v2.3]$ rm -f /data1/k17kh03b/k17kh03b_KVNTN_290024325_W5
[oper@localhost eavnconverge_v2.3]$ ./eavn_converge 16 /data1/k17kh03b/k17kh03b_KVNTN_290024325_W5
^C
[oper@localhost eavnconverge_v2.3]$ ./eavn_converge 16 /data1/k17kh03b/k17kh03b_KVNUS_290024325_W5
^C
[oper@localhost eavnconverge_v2.3]$ ./eavn_converge 16 /data1/k17kh03b/k17kh03b_KVNYS_290024325_W5
^C
[oper@localhost eavnconverge_v2.3]$ ll /data1/k17kh03b/
total 71441888
-rw-r--r-- 1 oper oper 24463638528 Nov  1 11:01 k17kh03b_KVNTN_290024325_W5
-rw-r--r-- 1 oper oper 24371544064 Nov  1 13:50 k17kh03b_KVNUS_290024325_W5
-rw-r--r-- 1 oper oper 24321310720 Nov  1 13:53 k17kh03b_KVNYS_290024325_W5
[oper@localhost eavnconverge_v2.3]$ rm -f /data1/k17kh03b/k17kh03b_KVNYS_290024325_W5
[oper@localhost eavnconverge_v2.3]$ ./eavn_converge 16 /data1/k17kh03b/k17kh03b_KVNYS_290024325_W5
^C
[oper@localhost eavnconverge_v2.3]$ ipcs

------ Message Queues --------
key        msqid      owner      perms      used-bytes   messages

------ Shared Memory Segments --------
key        shmid      owner      perms      bytes      nattch     status
0x0001619c 5406720    oper       777        16744448   0
0x0001d529 5439489    oper       777        16744448   0
0x000b722b 5472258    oper       777        16         0

------ Semaphore Arrays --------
key        semid      owner      perms      nsems
0x00538002 1179648    oper       666        1

[oper@localhost eavnconverge_v2.3]$ ll /data1/k17kh03b/
total 71433712
-rw-r--r-- 1 oper oper 24463638528 Nov  1 11:01 k17kh03b_KVNTN_290024325_W5
-rw-r--r-- 1 oper oper 24371544064 Nov  1 13:50 k17kh03b_KVNUS_290024325_W5
-rw-r--r-- 1 oper oper 24312938496 Nov  2 20:37 k17kh03b_KVNYS_290024325_W5
[oper@localhost eavnconverge_v2.3]$
```

```
------ Semaphore Arrays --------
key        semid      owner      perms      nsems

[oper@localhost bin]$ ./kavafil_gpu 0 16 1 16 95.0 /data0/k17kh03b/k17kh03b_KVNYS_290024318.vdif 1495559072 /data1/k17kh03b/k17kh03b_KVNYS_290024325
GPU Device 0: "TITAN V" with compute capability 7.0

SAMPLEFILEBYTELEN(4202464), TOTALSAMPLELEN(16744448)
Measured time for parallel execution = 106.718s
Test passed
[oper@localhost bin]$
```

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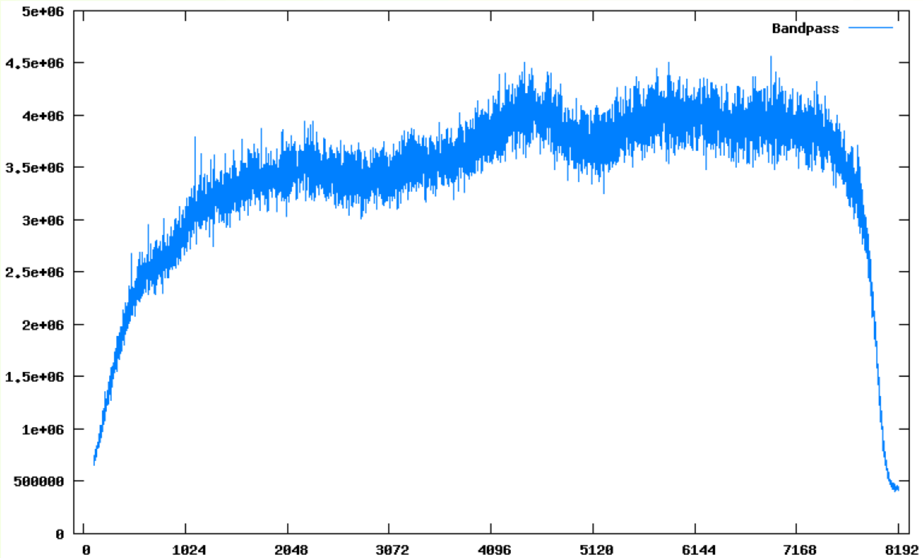
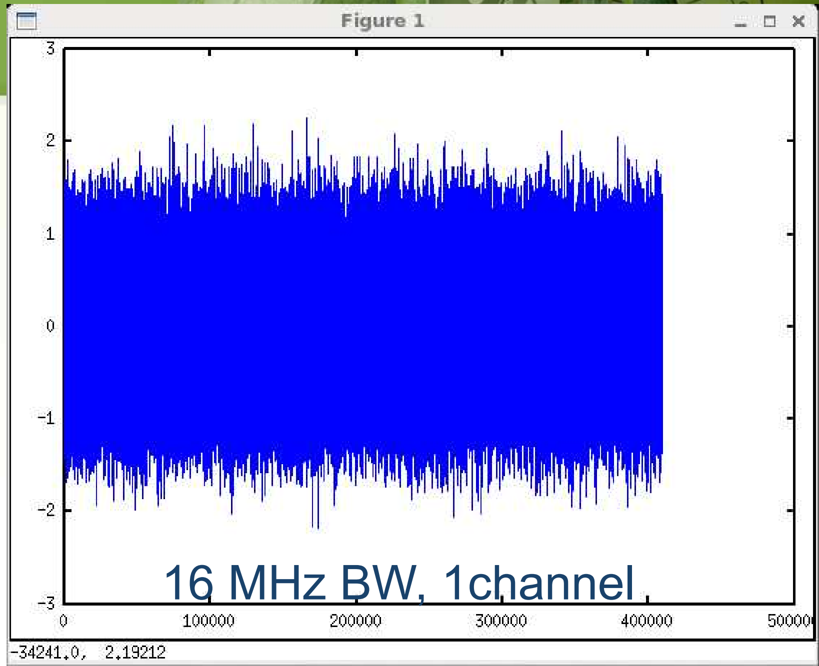
# Filtering Result

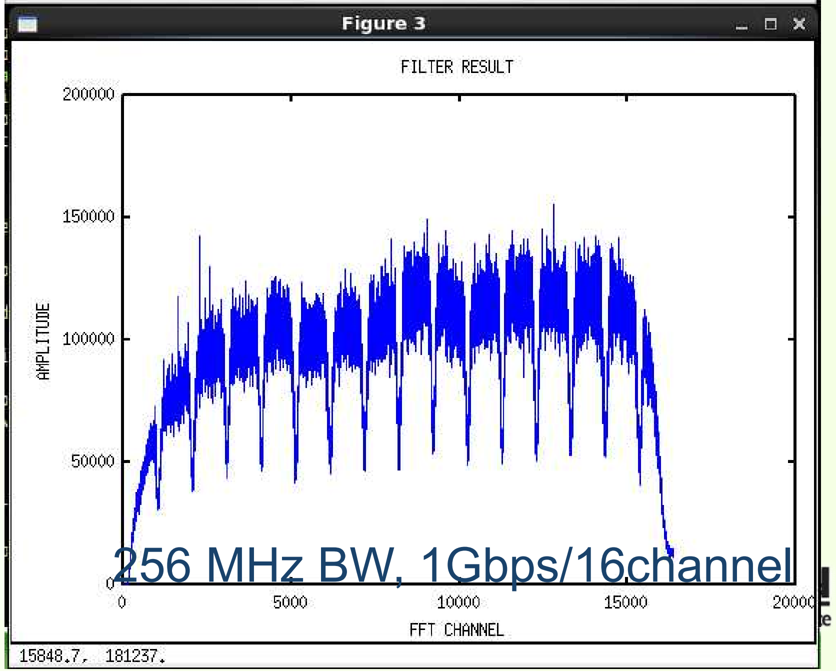
- Image Plot with OCTAVE




512 MHz BW, 2Gbps/1channel



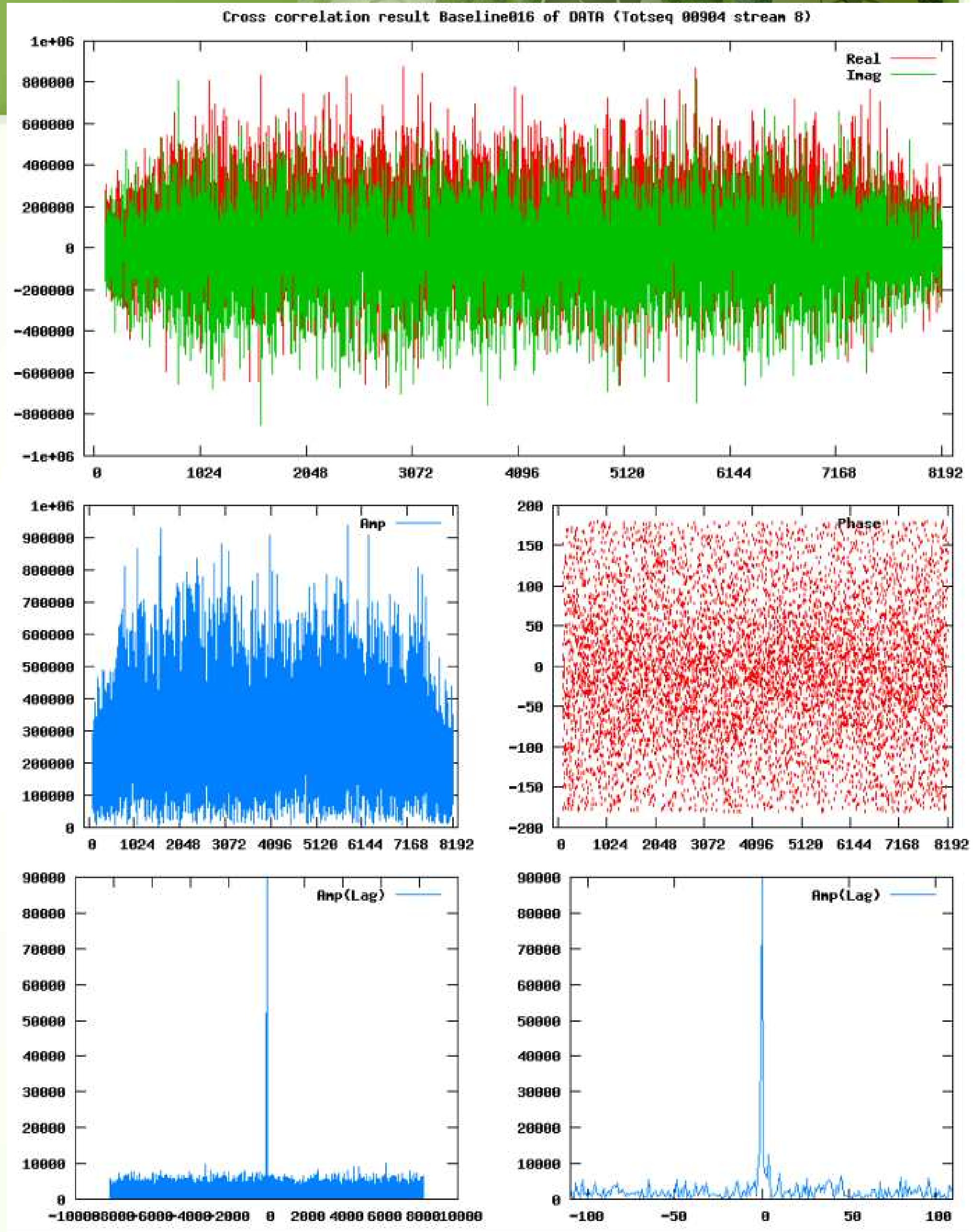

16 MHz BW, 1channel




256 MHz BW, 1Gbps/16channel

# Preliminary Result1

- **R17289c**
  - 2Gbps (512 MHz BW), 1 channel, KVN 3 stations data was filtered and used for correlation.
  - SW correlation was conducted.
  - In this result, only KVN Tamna – Ulsan Baseline is displayed.

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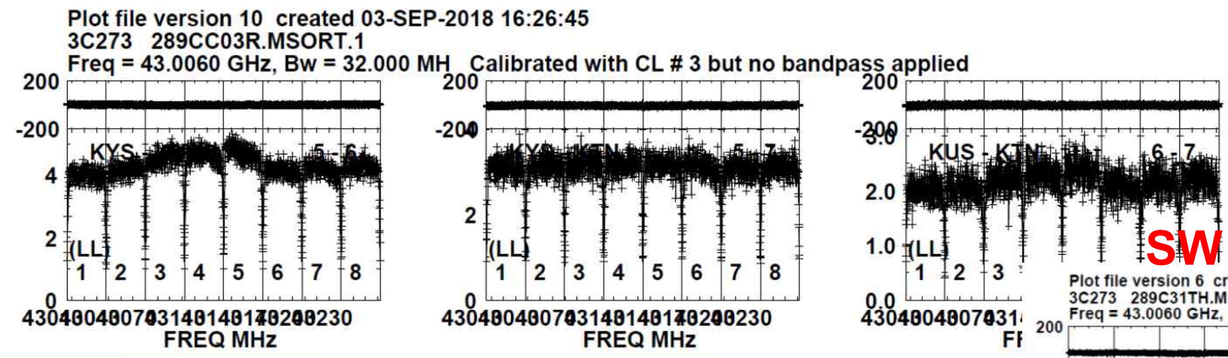
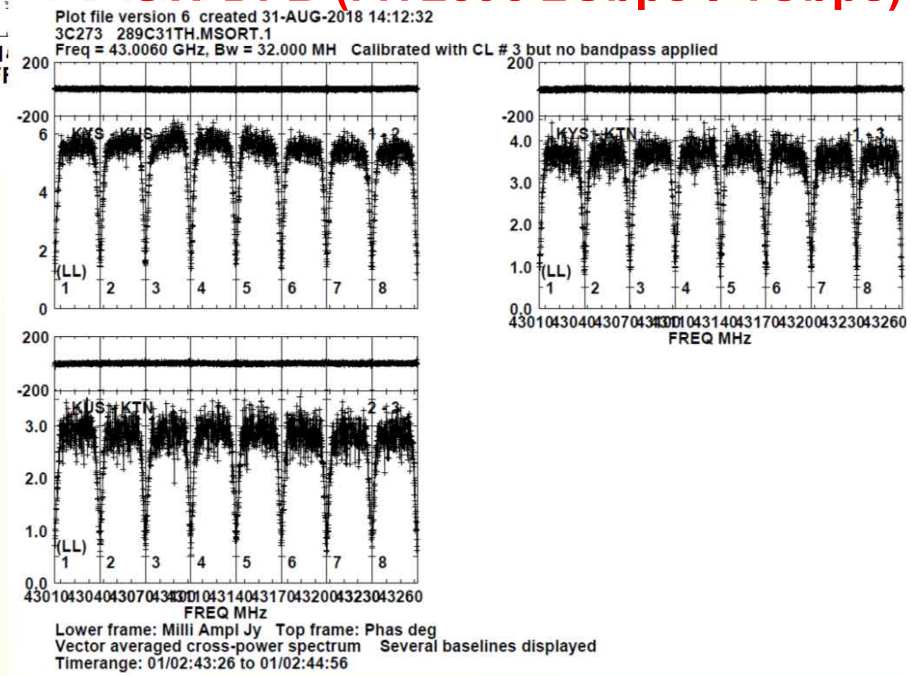
# Preliminary Result2

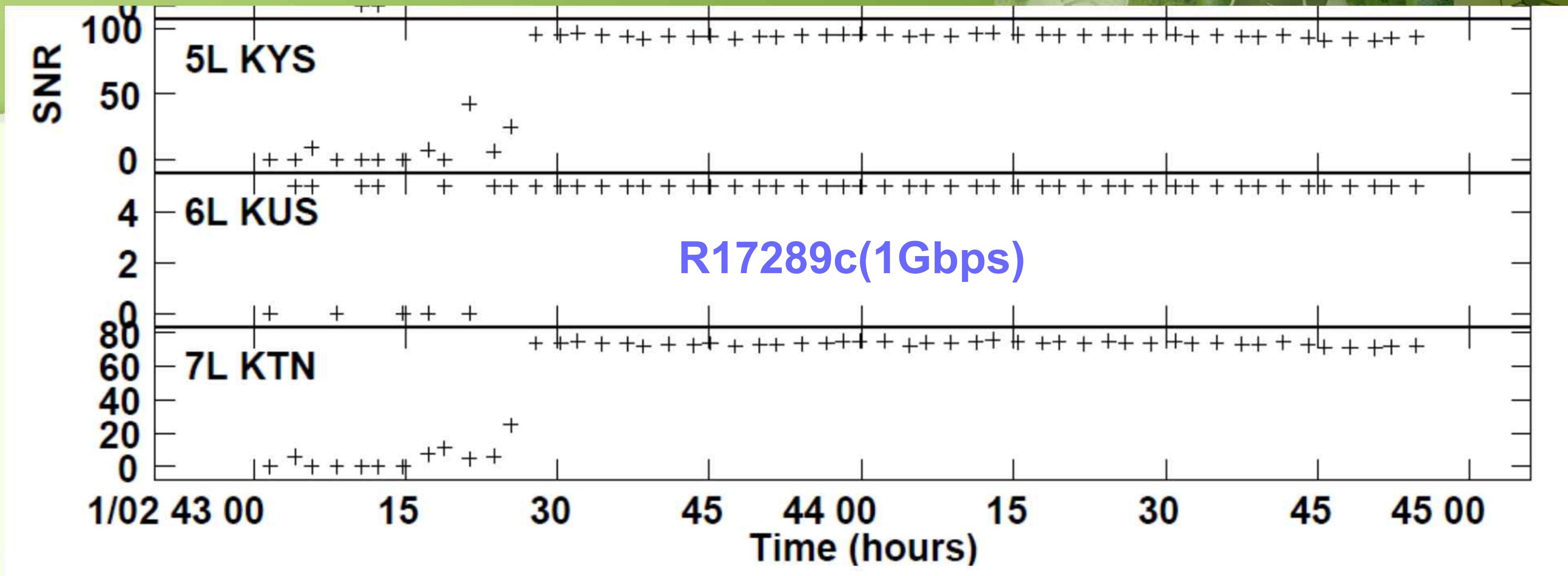
- To confirm the SW DF performance in data analysis with AIPS
- Correlation was conducted for the same data.

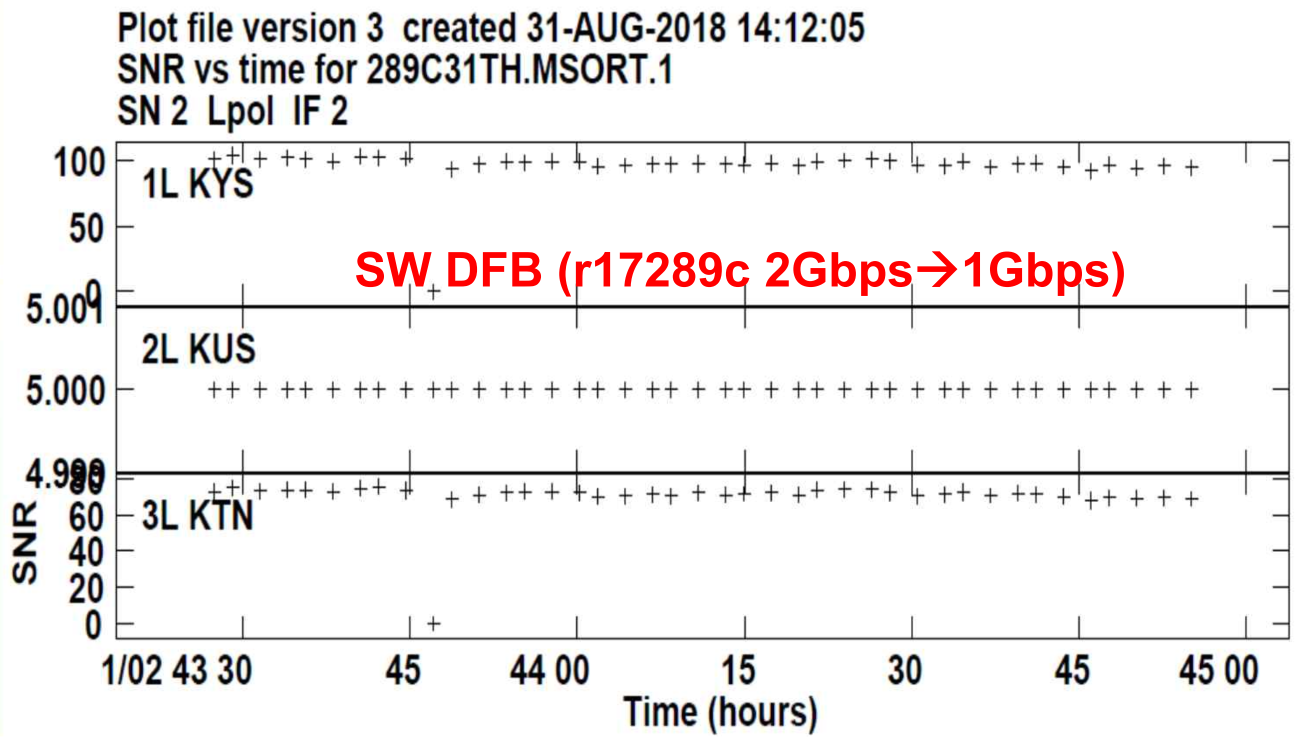



R17289c(1Gbps)

SW DFB (r17289c 2Gbps→1Gbps)




R17289c(1Gbps)
5L KYS
6L KUS
7L KTN
SNR
Time (hours)
1/02 43 00
15
30
45
44 00
45 00


Plot file version 3 created 31-AUG-2018 14:12:05
SNR vs time for 289C31TH.MSORT.1
SN 2 Lpol IF 2
SW DFB (r17289c 2Gbps→1Gbps)
1L KYS
2L KUS
3L KTN
SNR
Time (hours)
1/02 43 30
45
44 00
15
30
45 00

# Future works

- **Full data filtering for verification**
  - 1st : using KaVA data
  - 2nd : using EAVN especially with JVN
  - Detail comparison work is expected
  - Using Full data with SW DFB, the correlation will be scheduled
- **To reduce the processing time**
  - SW optimization and modification will be done for parallel processing with 2 GPU board.