VGOS with Continuous Frequency Coverage: The GALA-V Example

Mamoru Sekido, K.Takefuji, H.Ujihara, T.Kondo, M.Tsutsumi, Y.Miyauchi, E.Kawai, S.Hasegawa, R.Ichikawa, Y.Koyama, Y.Hanado, J.Komuro, K.Terada, K.Namba, R.Takahashi, K.Okamoto, T.Aoki, T.Ikeda (NICT)

K.Watabe, T.Suzuyama (AIST/NMIJ)

R.Kawabata, M.Ishimoto, T. Wakasugi (GSI)

Our experiences

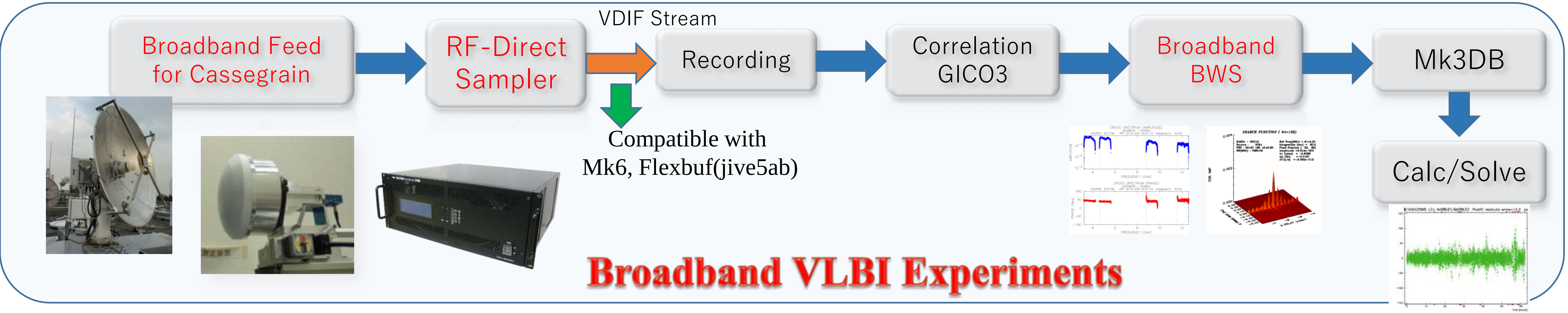
1. **Broadband VLBI is tolerant to RFI**
2. **Subpico-second delay precision is enabled even with small (1.6-2.4m) antenna pair.**

   Please imagine what happens with VGOS telescopes!

   It is encouraging future of VGOS.
3. **RF Direct Sampling enables stable Broadband group delay measurement (Pcal free).**

Contents of this Presentation

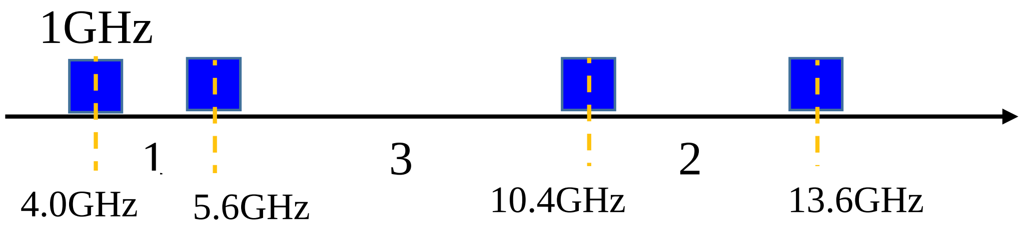
- **Components of the GALA-V System**
  - Broadband Feed and Antenna performance
  - RF-Direct Sampling
  - Broadband Bandwidth Synthesis and Phase Calibration with radio source
  - RFI Survey and Current condition
- **Broadband VLBI Experiments**
  - Delay measurement precision
  - Geodetic Solution and our Clock comparison

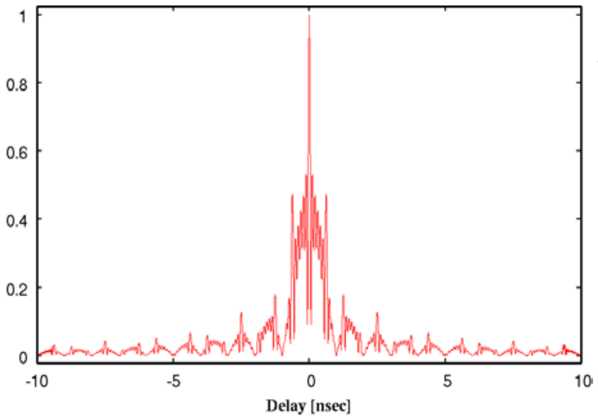


GALA-V Project Overview

Frequency comparison by using Transportable Broadband telescopes

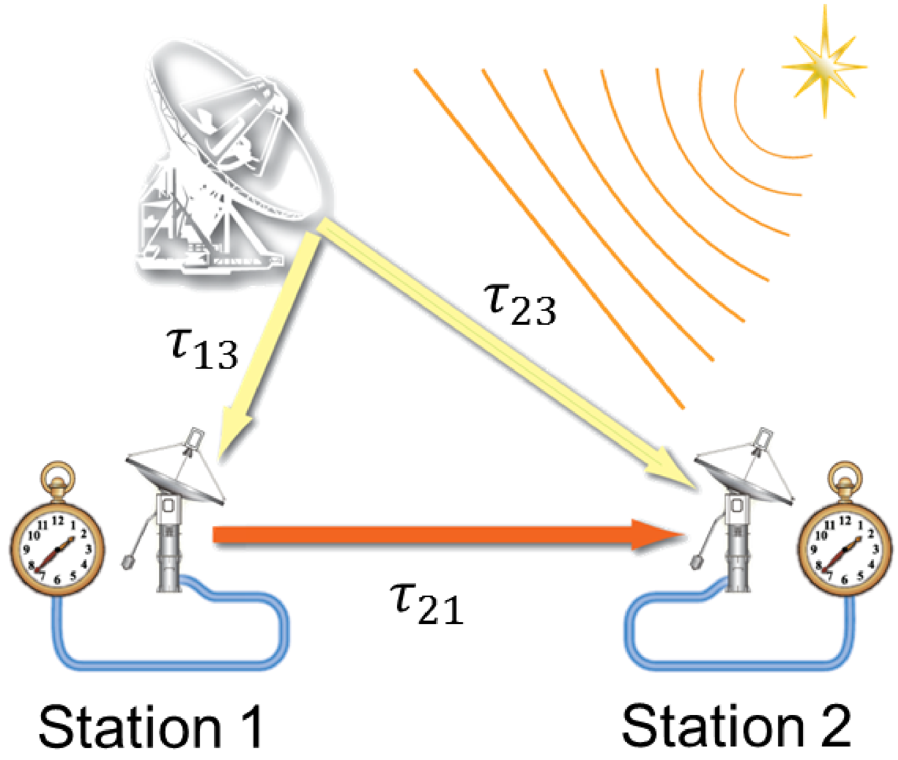
- VLBI Sensitivity :VLBI Sensitivity=$\propto D_1 D_2 \sqrt{BT}$
  B: 32MHz → 1024MHz (32 times)
- Radio Frequency： 3-14 GHz
- Data Acquisition： 4 band (1024 MHz width)
  - Fc=4.0GHz, 5.6GHz, 10.4GHz, 13.6GHz
  - Effective Bandwidth：3.8GHz (10 times more than Conventional)





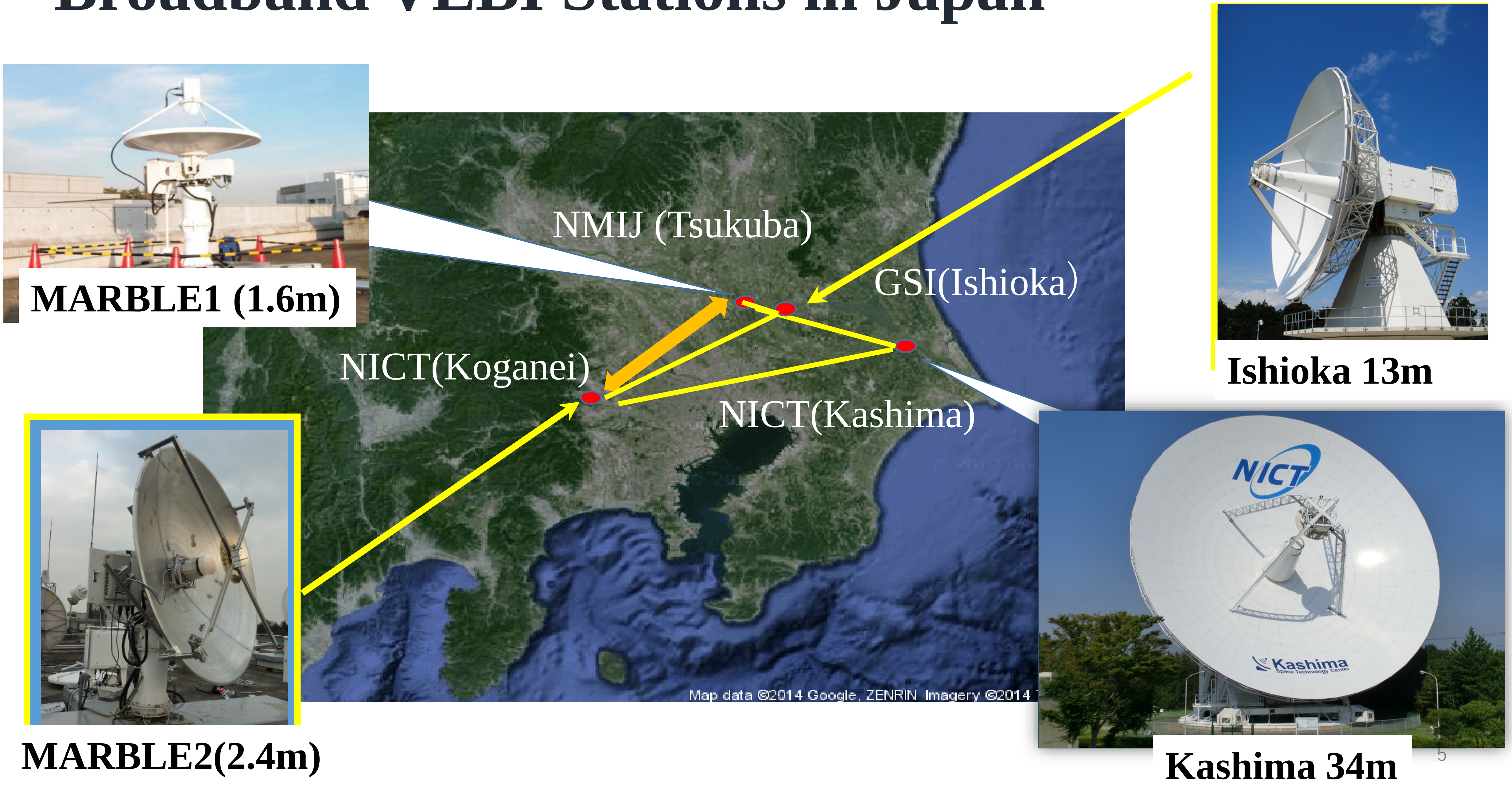
Delay Resolution Function

10 time higher resolution will be gained by broader bandwidth



$$\tau_{21} = \tau_{13} - \tau_{23}$$

Broadband VLBI Stations in Japan



Initial State of Broadband Gala-V Project

Kashima 34m

MARBLE1 1.6m
@NMIJ(Tsukuba)

MARBLE12 1.5m
@Konganei

Original broadband Feed
NINJA, IGUANA-H

Rindgren
QRHA

Broadband Gala-V Project of Today's Talk

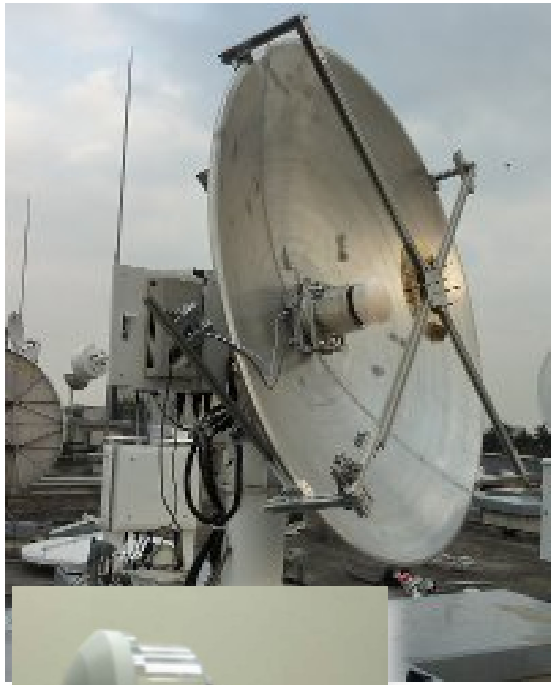
Kashima 34m

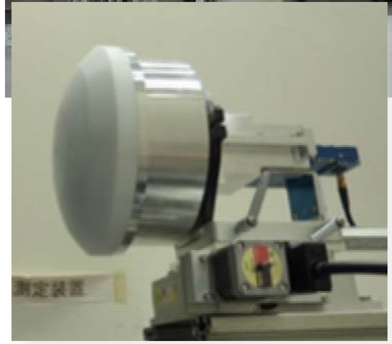
Broadband Feed
NINJA

MARBLE1 1.6m
@NMIJ(Tsukuba)

Rindgren
QRHA

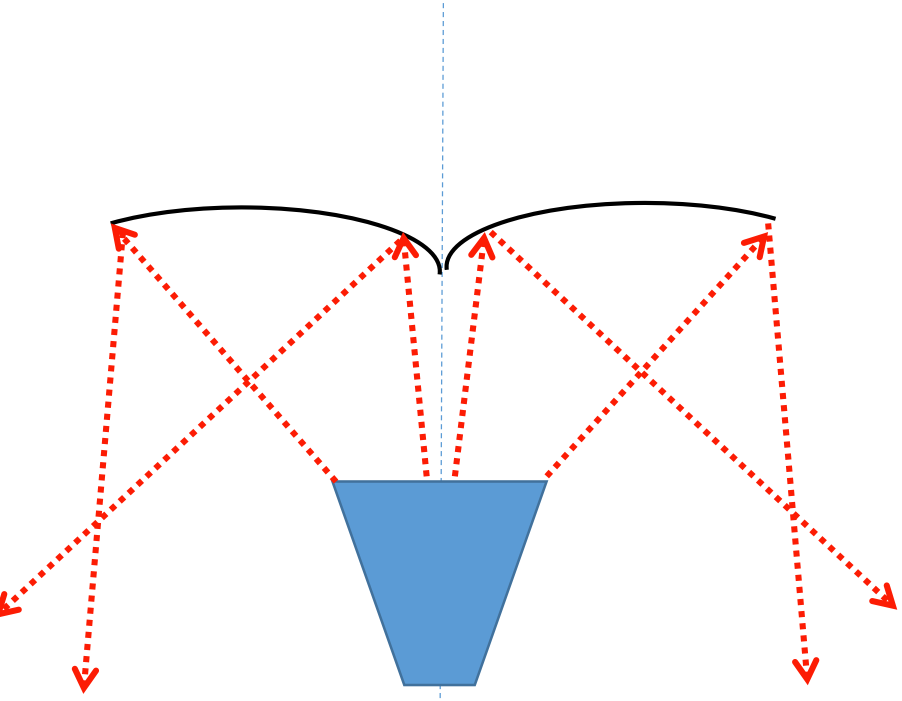
MARBLE12 2.4m
@Konganei



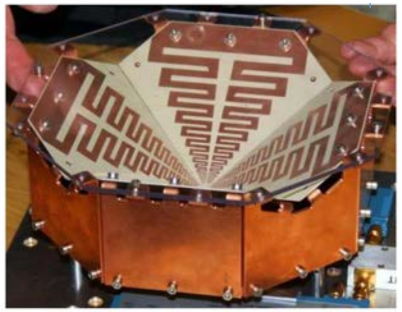


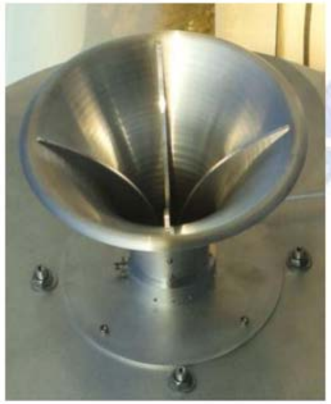
NINJA Feed
For Marble

Reason why NICT Developed own Broadband Feeds

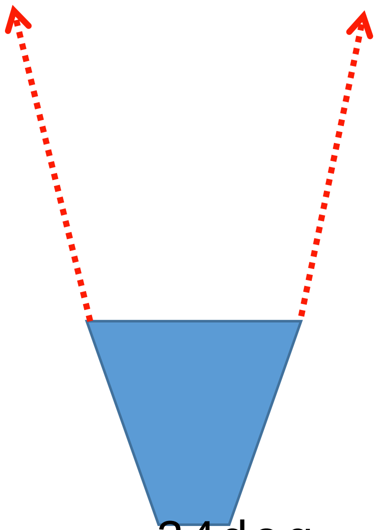


~120deg.

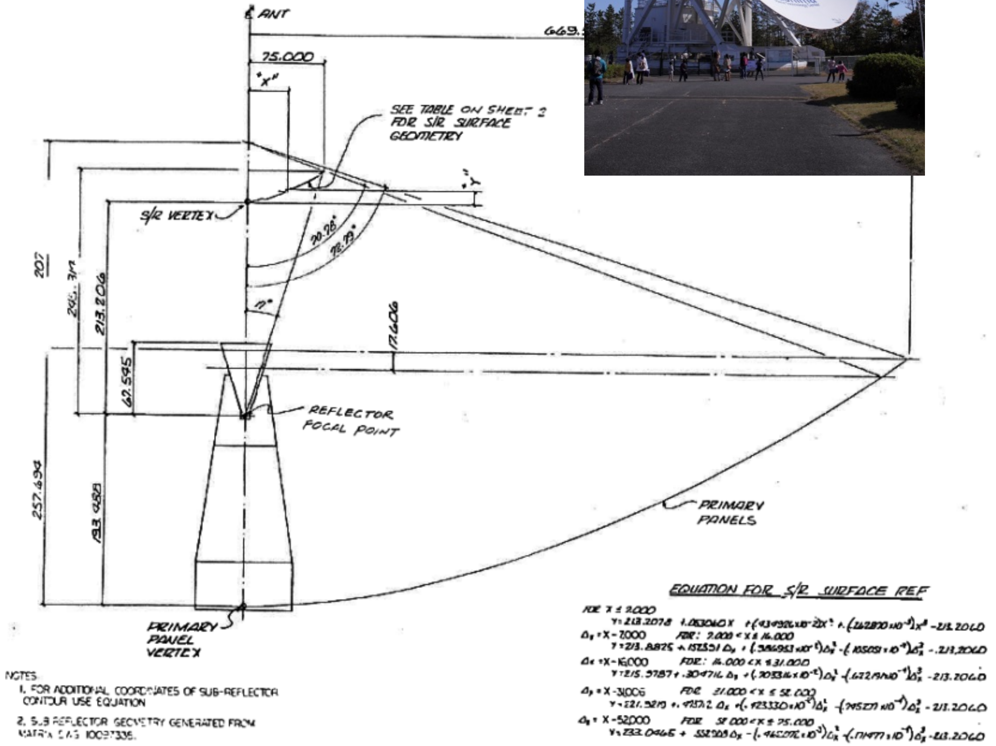


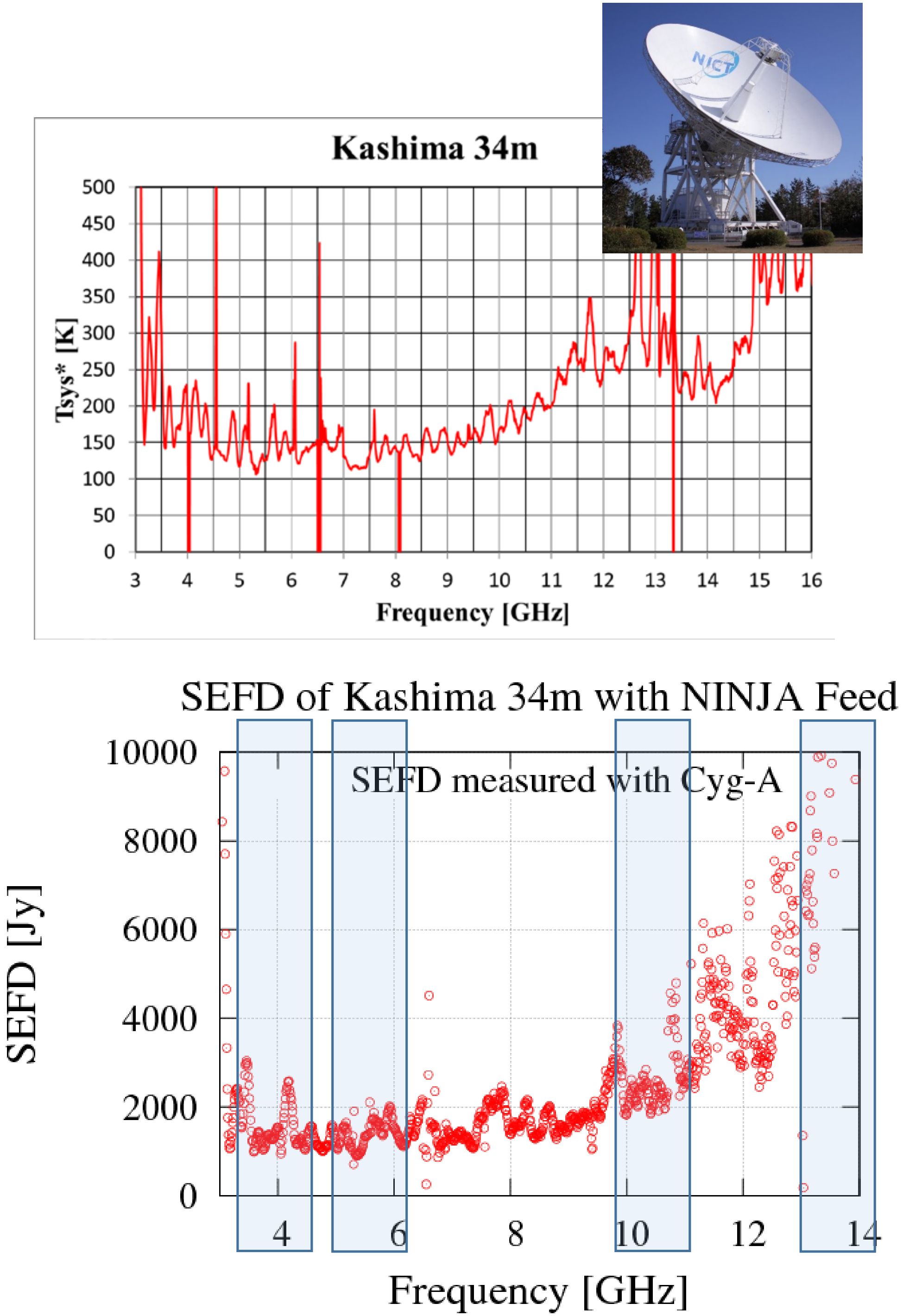


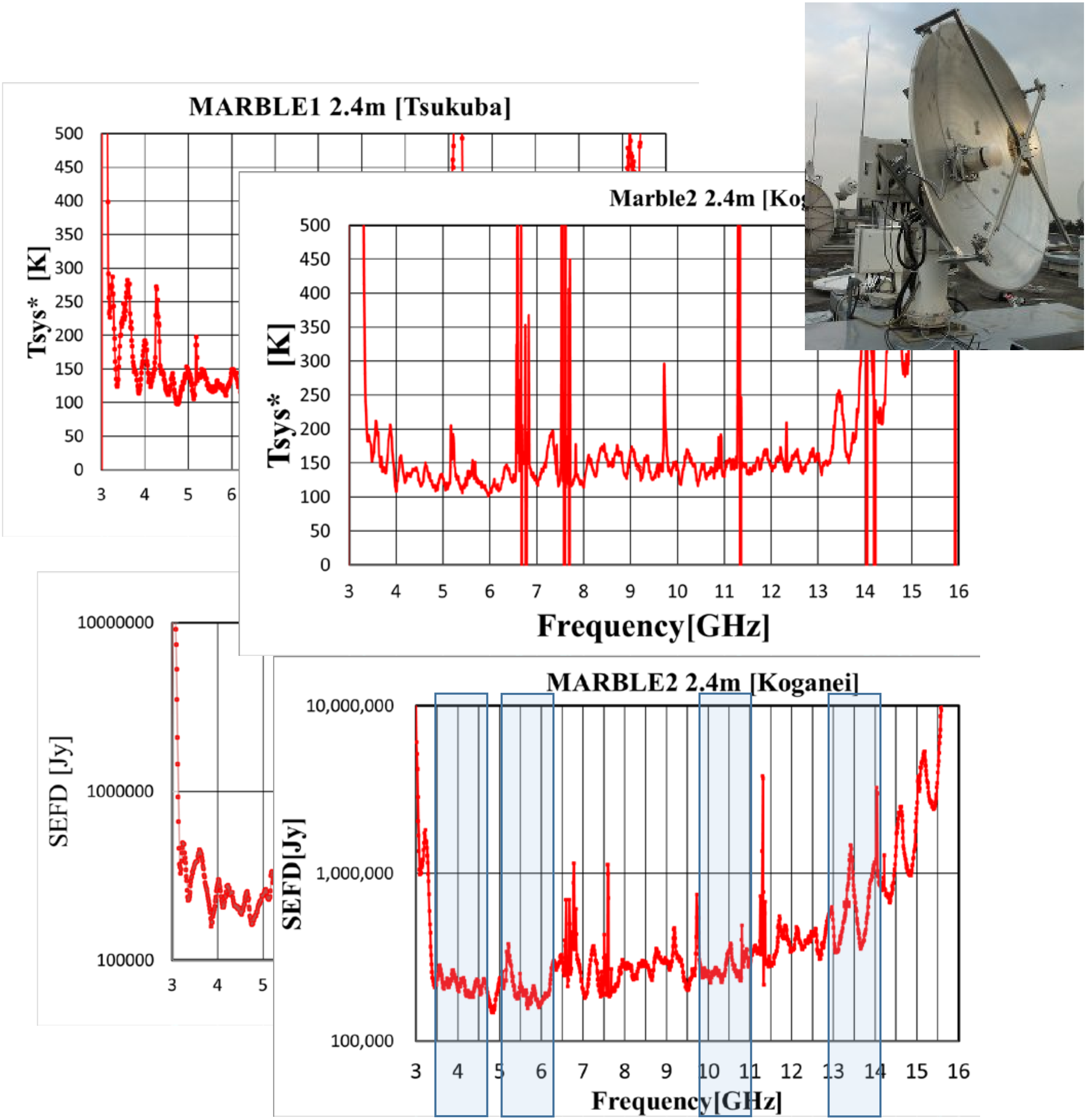
Requirement of
Broadband Frequency
and **Narrow beam width**



~34deg.



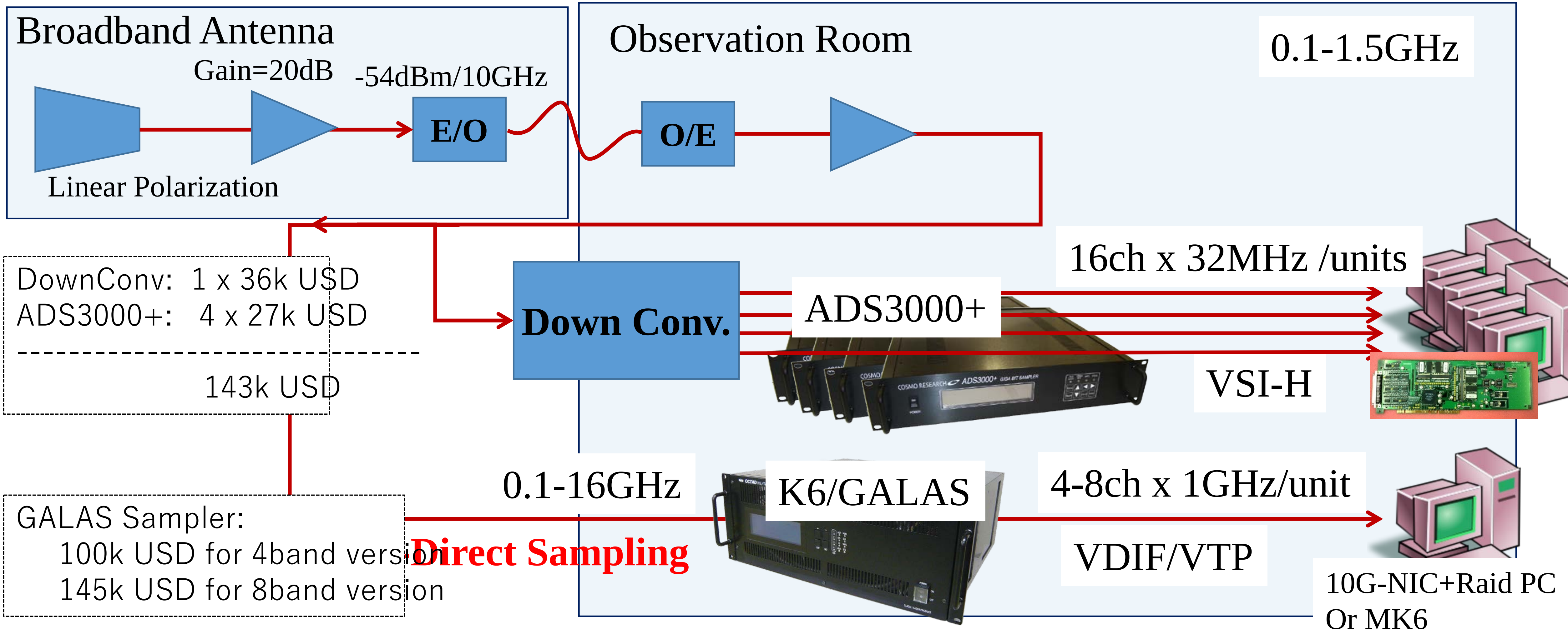

Kashima 34m
NICT
Tsys* [K]
Frequency [GHz]
SEFD of Kashima 34m with NINJA Feed
SEFD measured with Cyg-A
SEFD [Jy]
Frequency [GHz]


MARBLE1 2.4m [Tsukuba]
Tsys* [K]
Marble2 2.4m [Ko
Tsys* [K]
Frequency[GHz]
SEFD [Jy]
MARBLE2 2.4m [Koganei]
SEFD[Jy]
Frequency[GHz]

Data Acquisition System

300k=-174 dBm/Hz
-74dBm/10GHz

We have to be careful to compromise (1)avoiding saturation of system and (2) increase of noise figure, as discussed by Chris(2012) .



RF-Direct Sampling and DBBC

IF Input Port	2
Input Freq. Range	0.1-16.4 GHz
Input port	**2 -4 analog input**
Sampling Rate	**16384 MHz sampling** **3bit**
Data mode	**DBBC to select 1GHz band by 1MHz step** **Nch/unit= 4 or 8** 2048 Msps/ch Qbit=1, or 2 bit
Output Port	10GBASE-SR, 4port
Data rate	8192 Mbps/port

K6/GALAS(Octad-G)

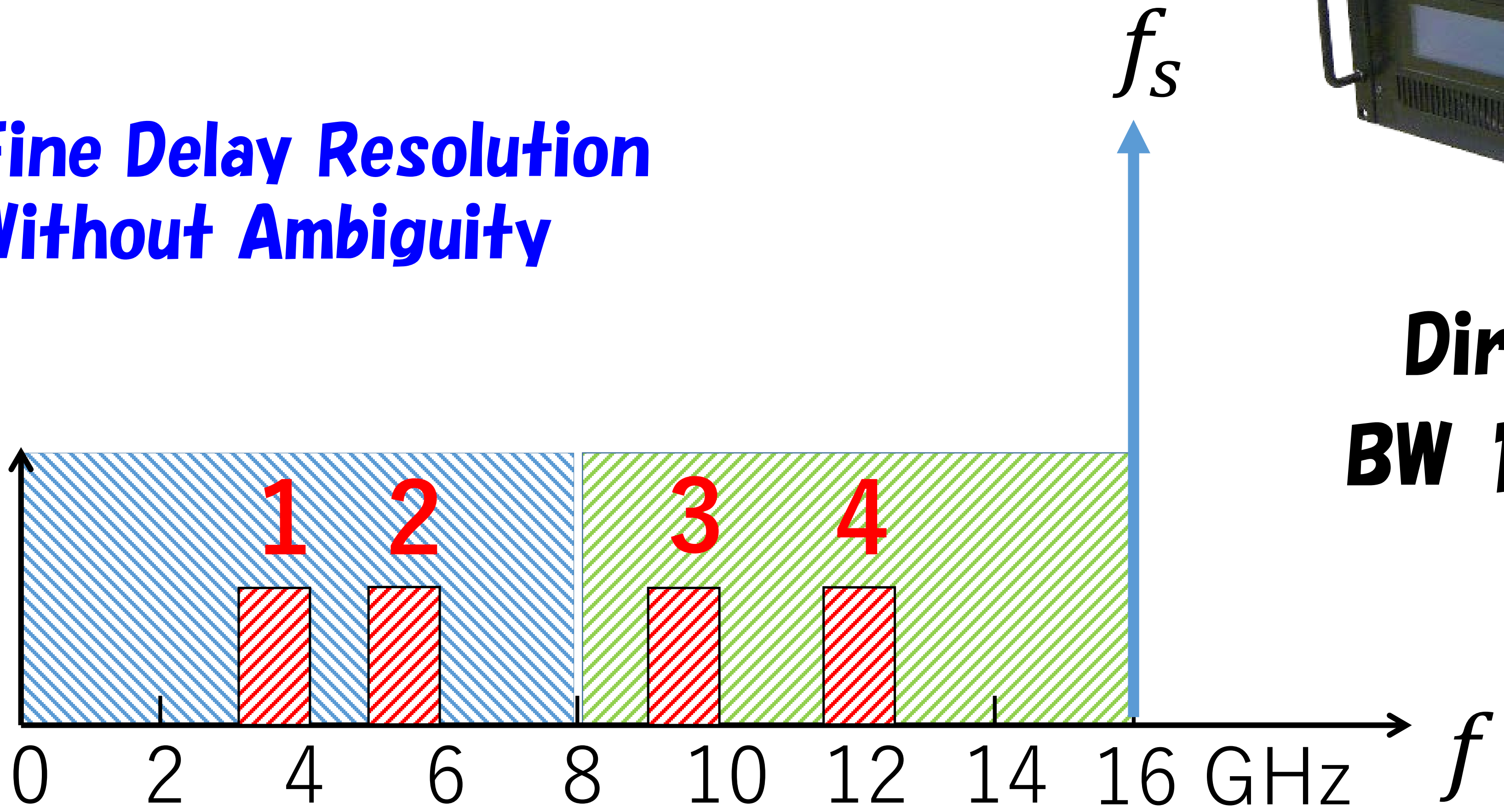
BW 1024MHz x 4-8ch

As close as Zero Redundancy

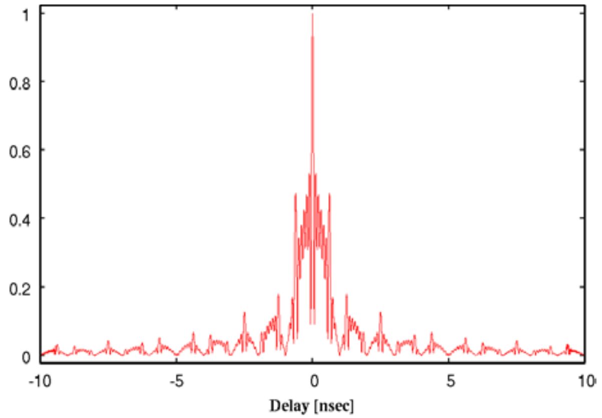
Frequency allocation

Fine Delay Resolution
Without Ambiguity

Direct Sampling
BW 1024MHz each



Lower Edge= 3.2, 4.8, 8.8, 11.6GHz

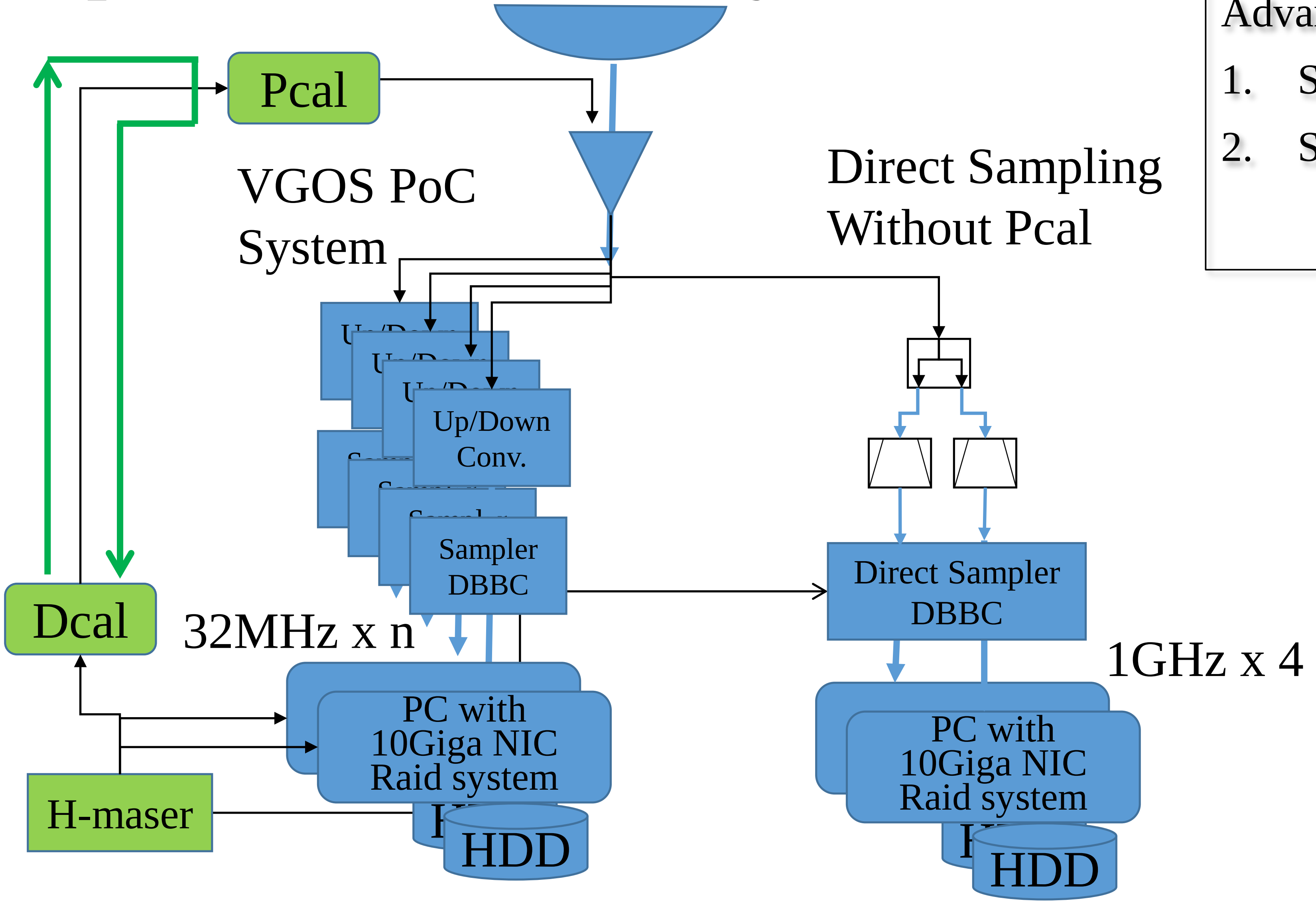


Advantages of Direct RF Sampling Technique possible Pcal-free system

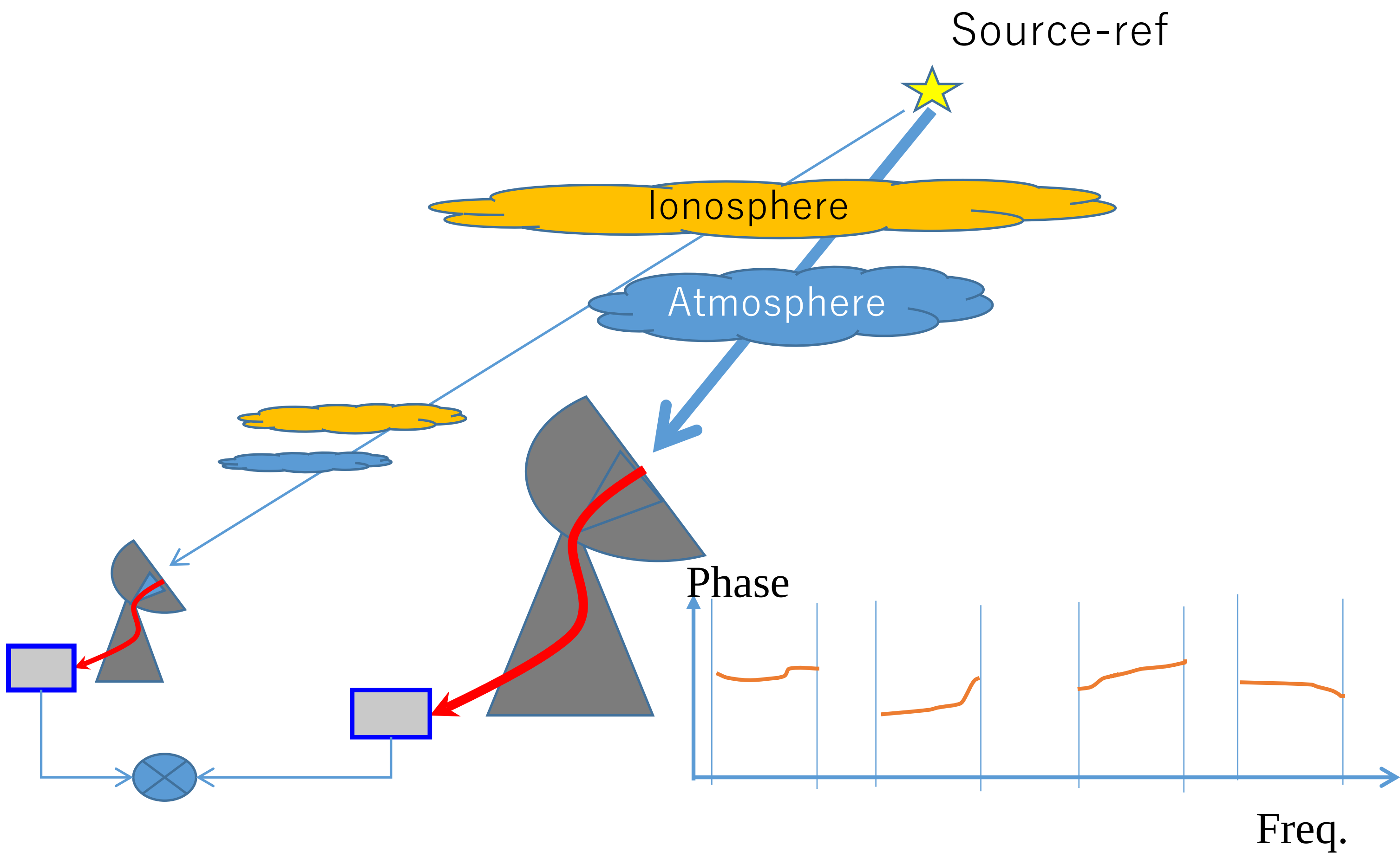
Advantages of Direct sampling

1. Simple and less system components.
2. Stable inter-band phase relation

   => (Pcal,Dcal free)

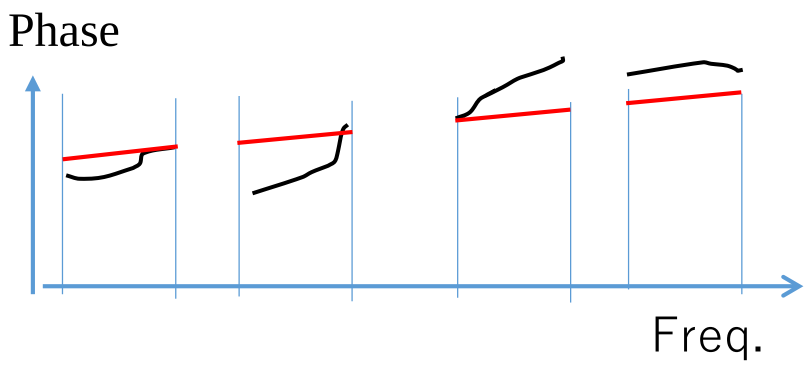


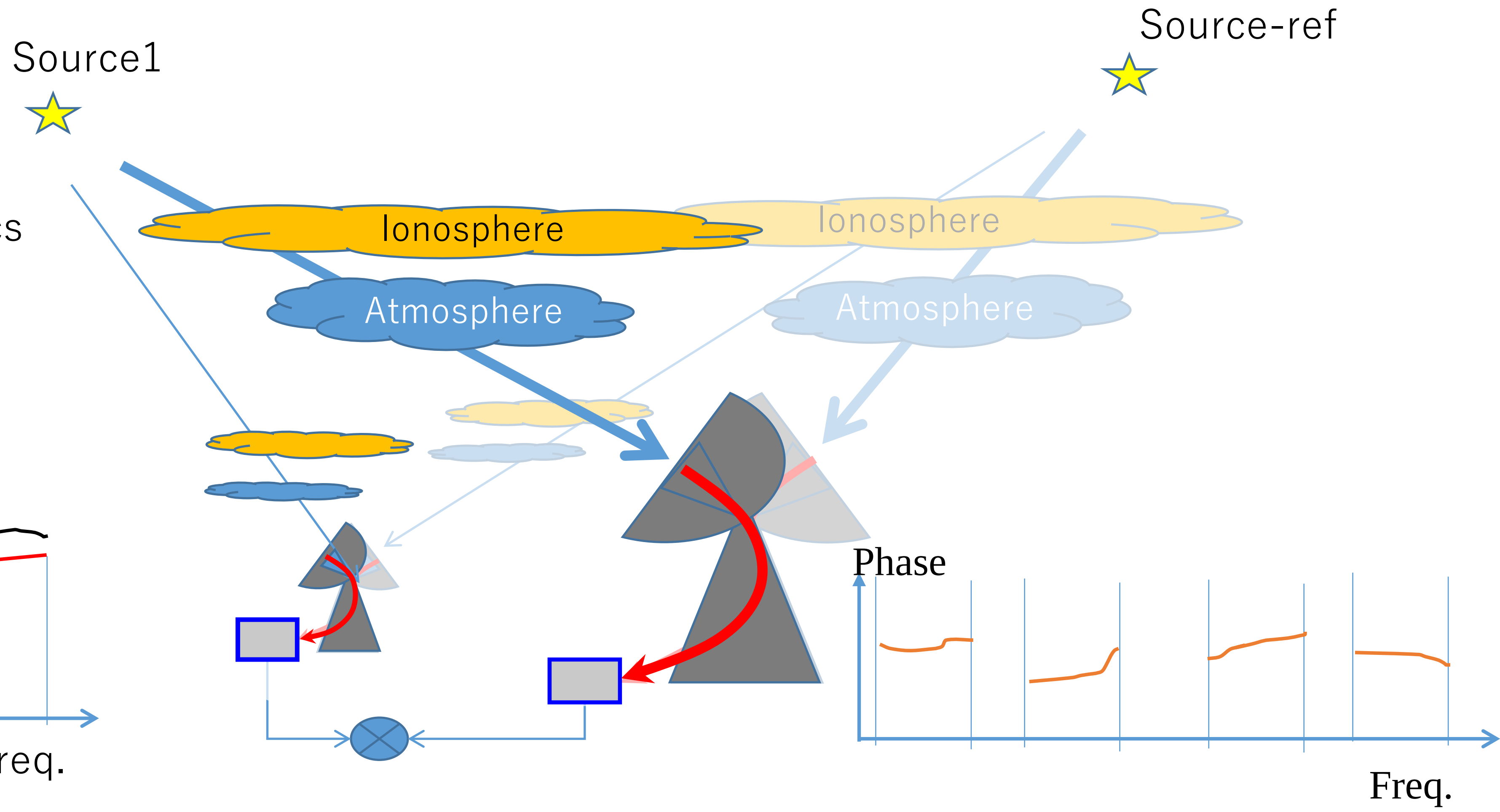
Procedure of Broadband Phase Calibration with radio source



Procedure of Broadband Phase Calibration with radio source

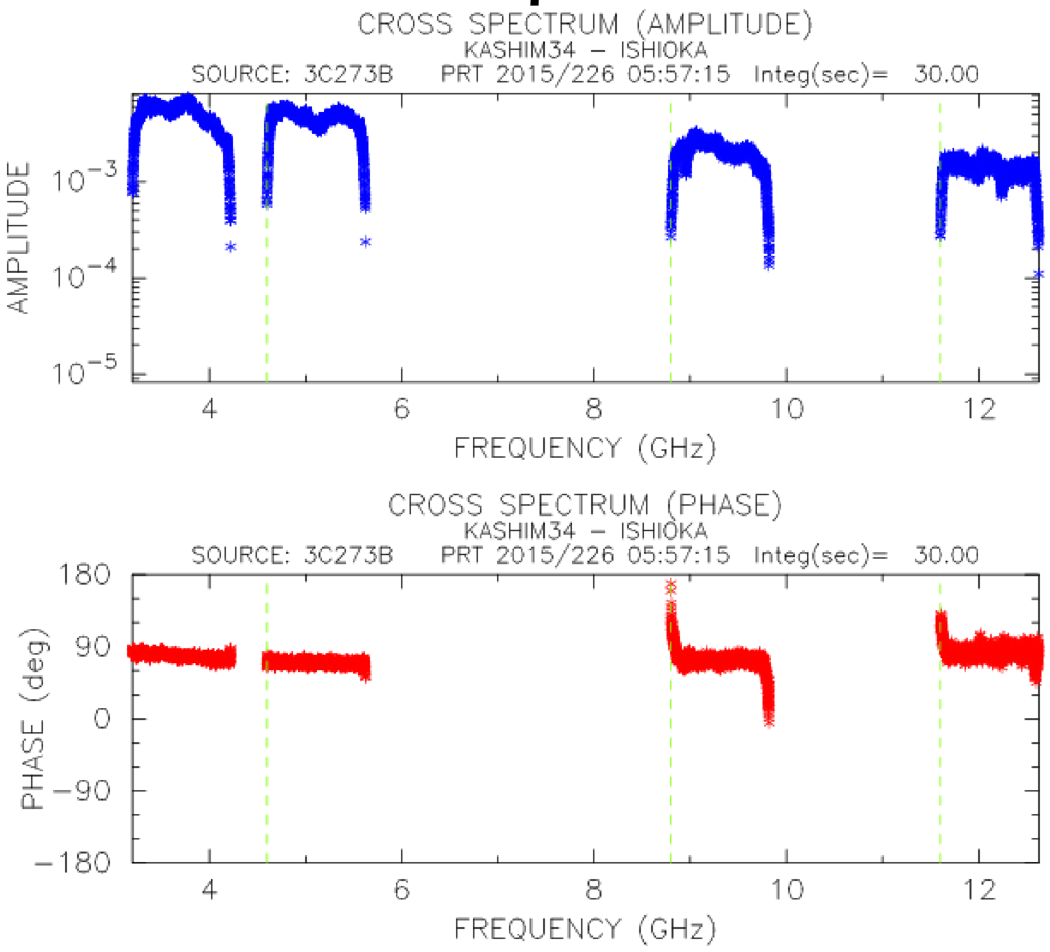
Signal path phase characteristics including feed are calibrated by using reference scan.



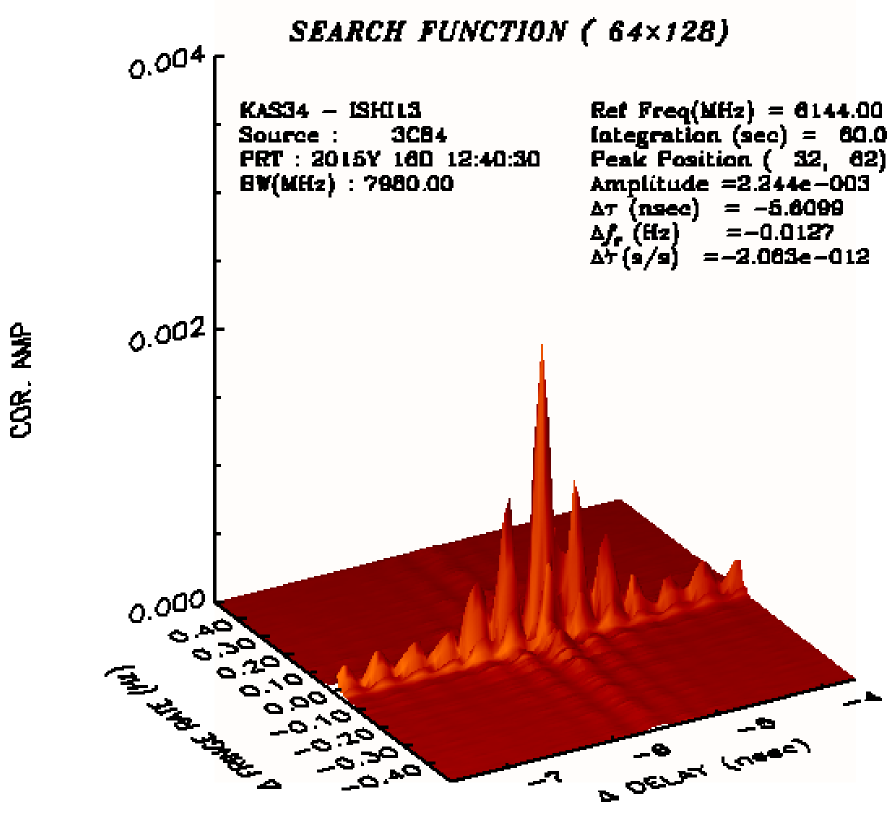


Full Bandwidth Synthesis #1-#(6-14GHz)

Cross Spectrum

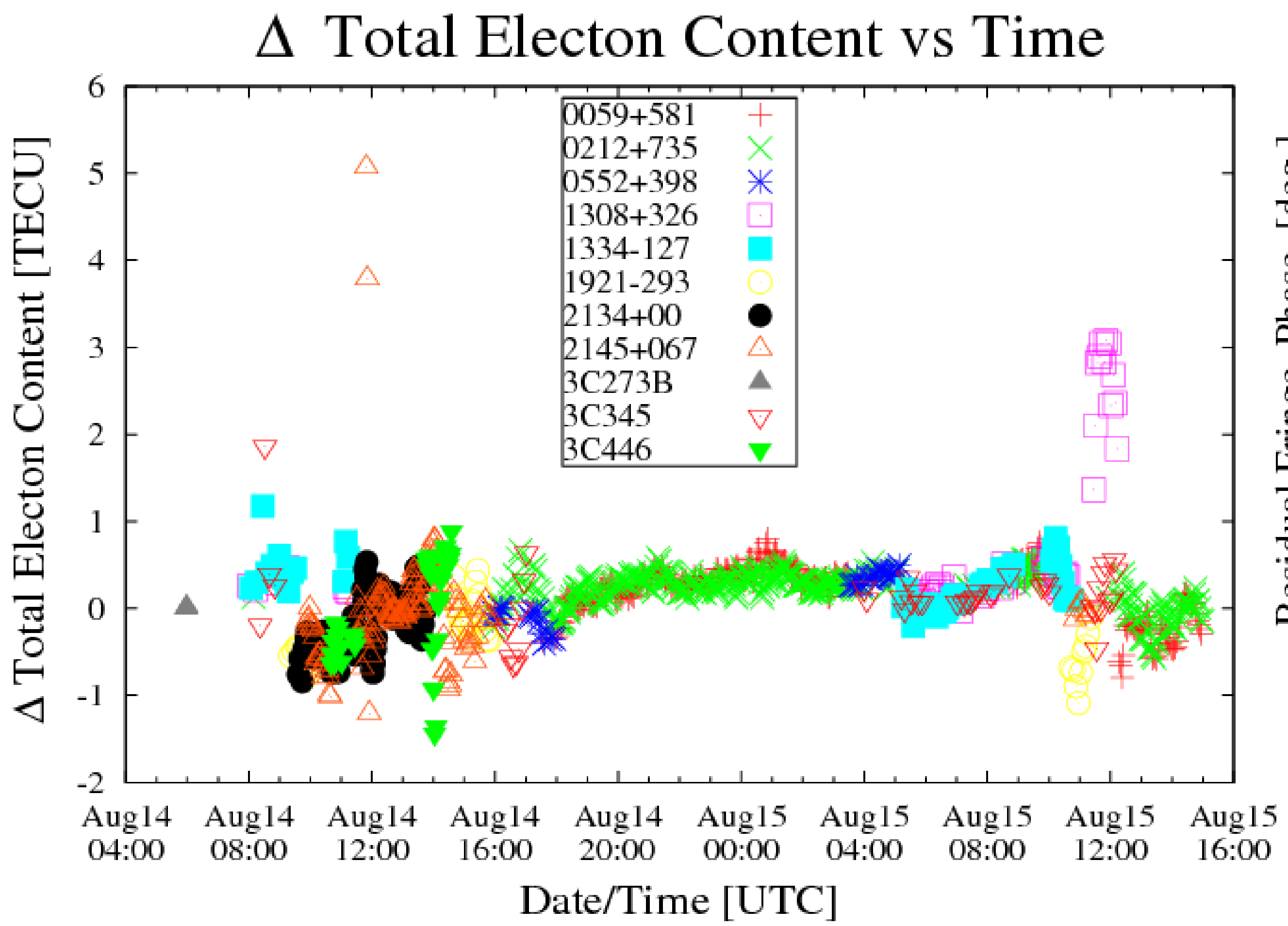


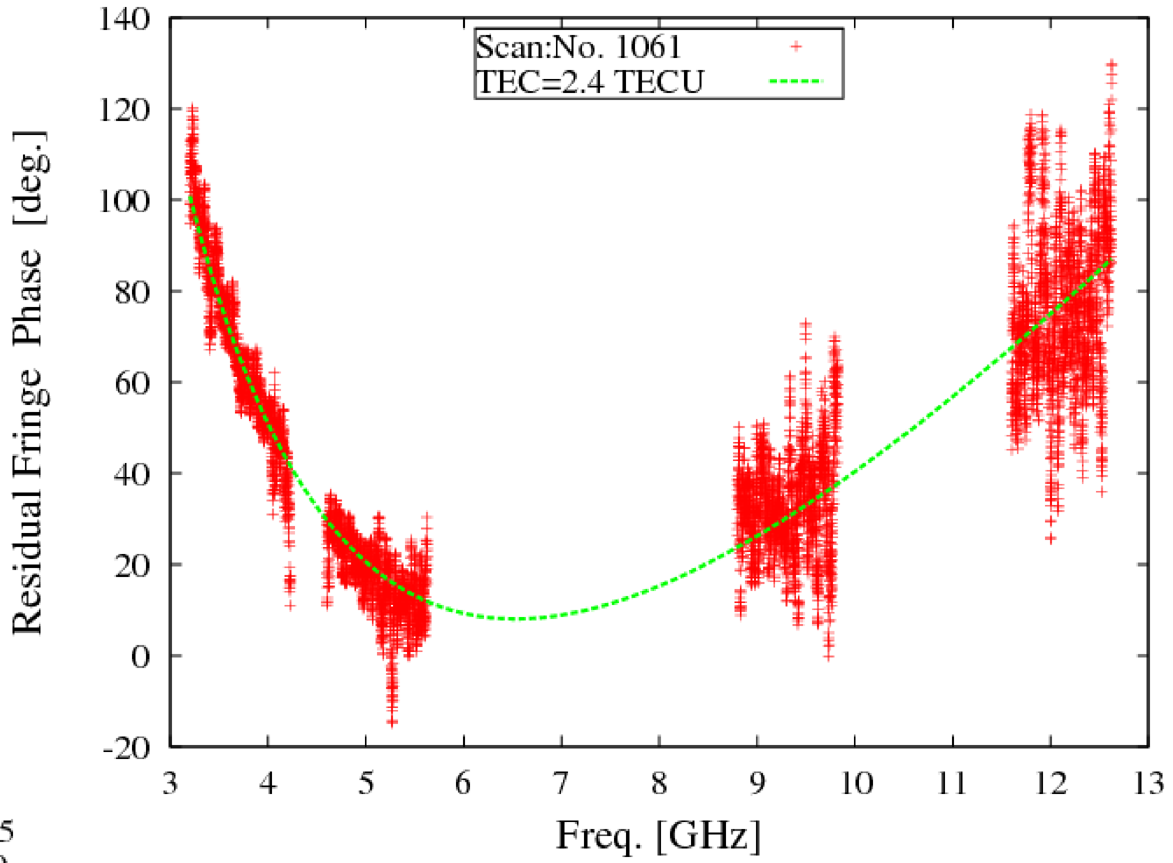
Delay Resolution Function



Least Square Estimation of δTEC and $\delta\tau$

$$\emptyset[deg.] = \alpha\frac{\delta TEC}{f} + 360 \times \delta\tau \times f + c$$





RFI Survey and Broadband DAS

Broadband RFI Survey Sites

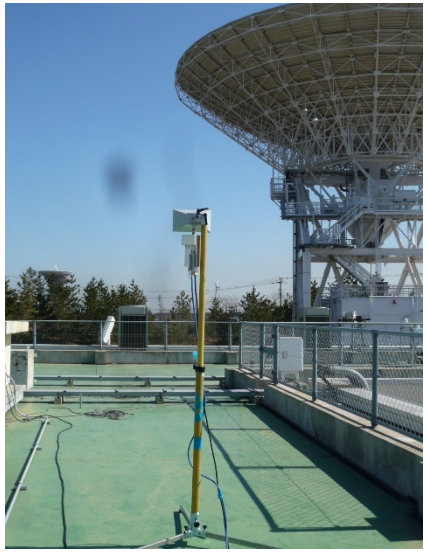
NICT-HQ(Koganei)

RF of 2nd Building. Communication Antenna for TWSFTT(14GHz), Other emission from experimental system of NICT Labs.

NMIJ(Tsukuba)

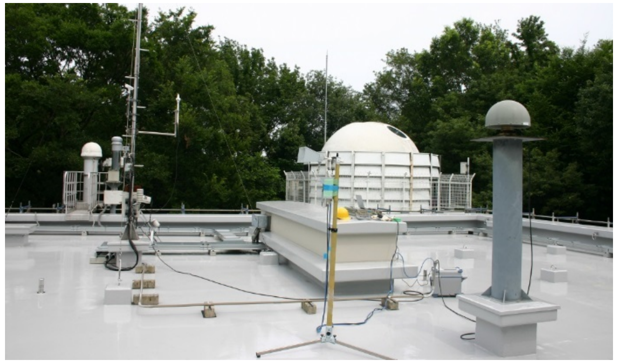
Communication Antenna for TWSFTT(not used).

NICT (Kashima)

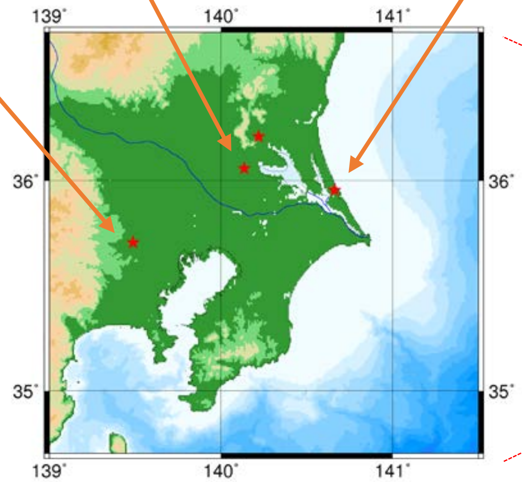


Roof Floor of Kashima 34m VLBI station Building.

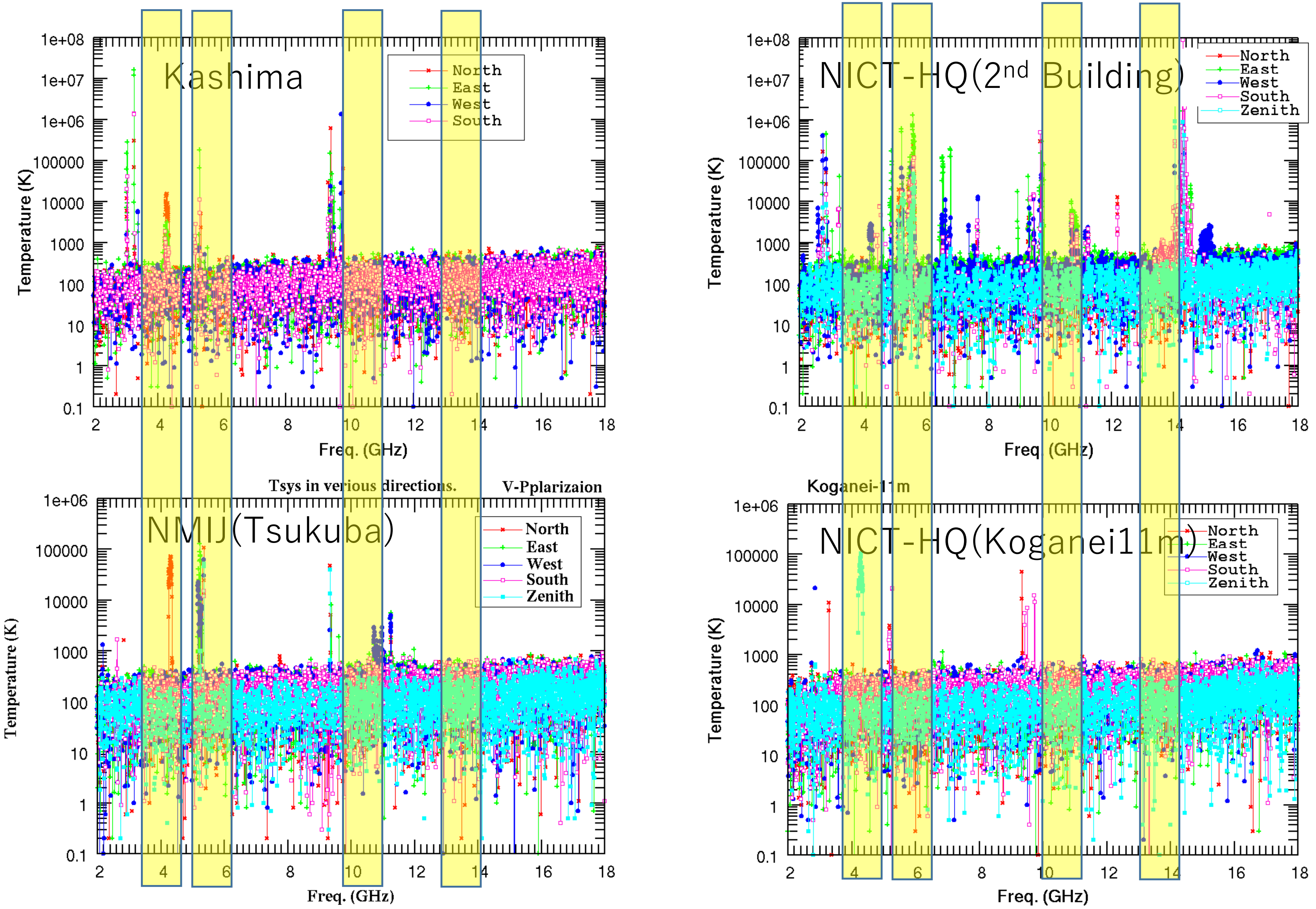
NICT-HQ(Koganei 11m)



Roof Floor of Koganei 11m VLBI station Building. Relatively quiet. Surrounded by trees.



RFI Survey at Tokyo,Kashima,Tsukuba



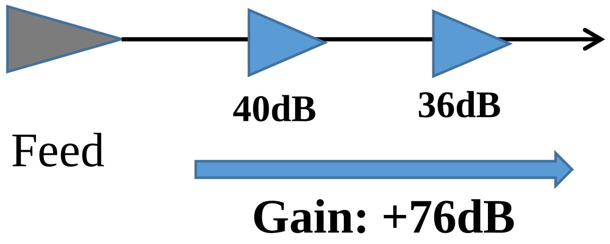
Our experience
“ we could make very precise delay measurement under RFI environment” should encourage VGOS future.

Advantage of RF-Direct Sampling - Robustness to RFI -

Power$= k_B T B$

Broadband (~ 10GHz) Case:

T=200K= **-176dBm/Hz = -101dBm/32MHz = -76dBm/10GHz**



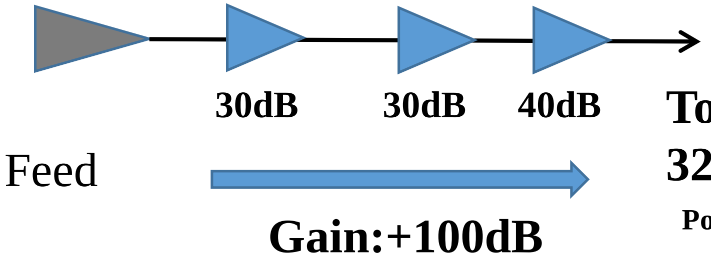
A/D Conv.

Total:

+0dBm@10GHz

Power density: -36dBm/MHz

Narrow Band (~ 32MHz) Case:



A/D Conv.

Total: +0dBm

32MHz

Power density: -16dBm/MHz

Case Study:

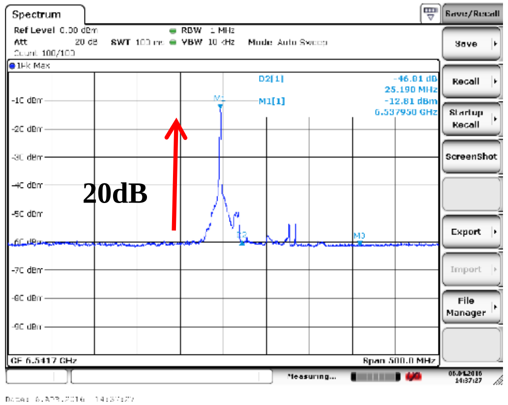
In the case RFI of +20dB up from noise floor with 1 MHz width.

Total Power of RFI Total Power of Signal

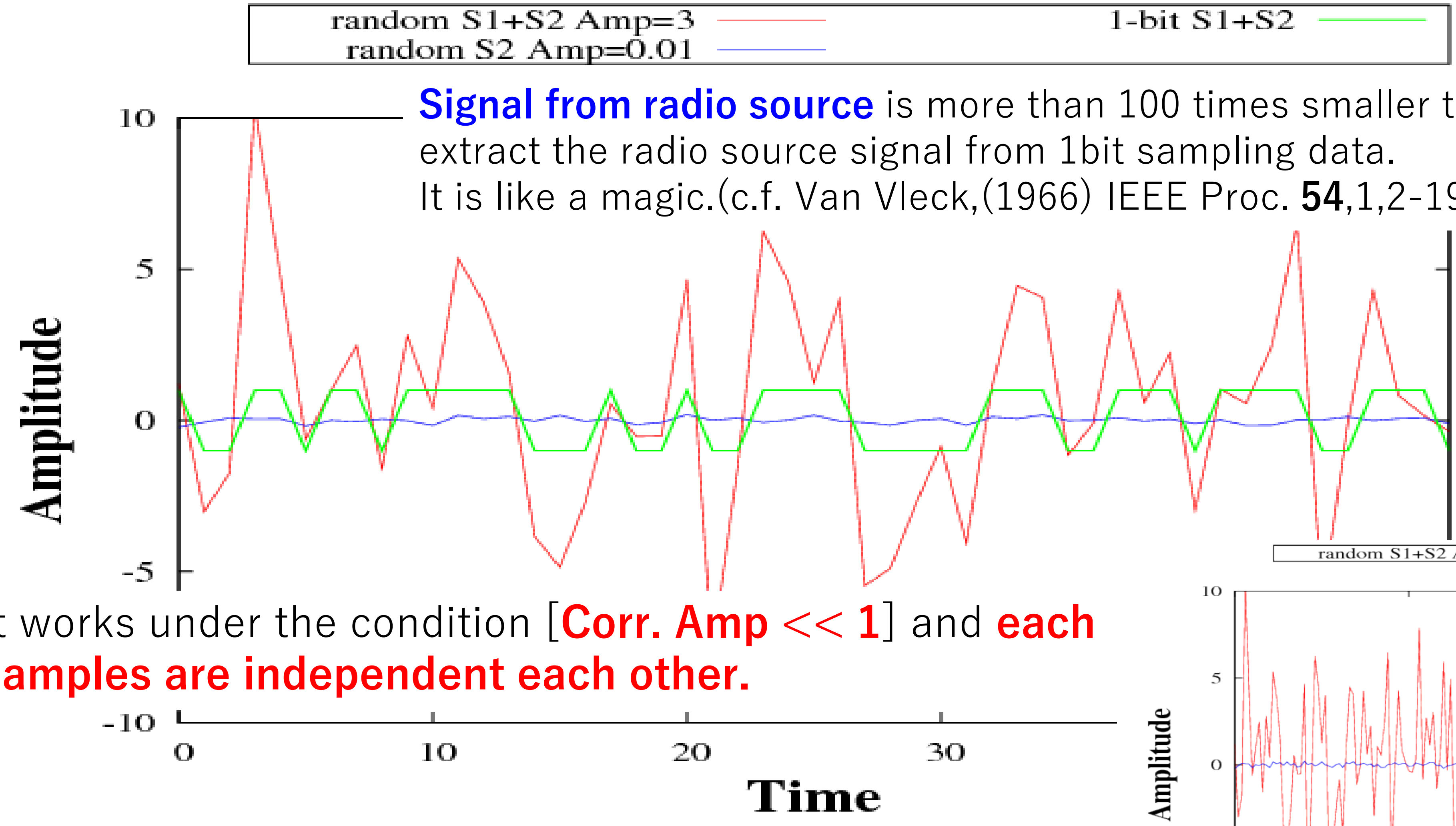
-20dBm < 0dBm

Total Power of RFI Total Power of Signal

+5dBm > 0dBm



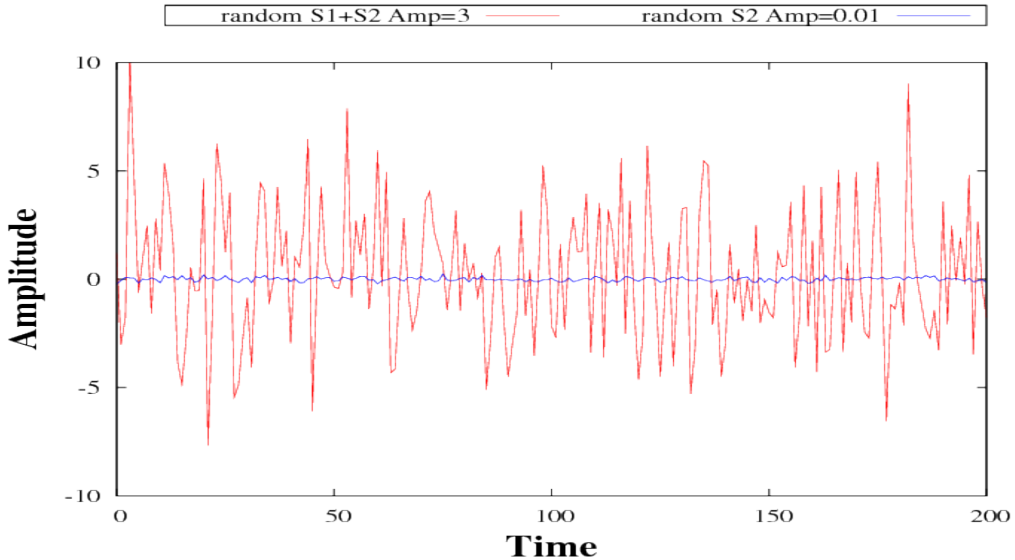
1bit sampling Simulation [noise(3)]



Signal from radio source is more than 100 times smaller than **noise,** but we can extract the radio source signal from 1bit sampling data.
It is like a magic.(c.f. Van Vleck,(1966) IEEE Proc. **54**,1,2-19)

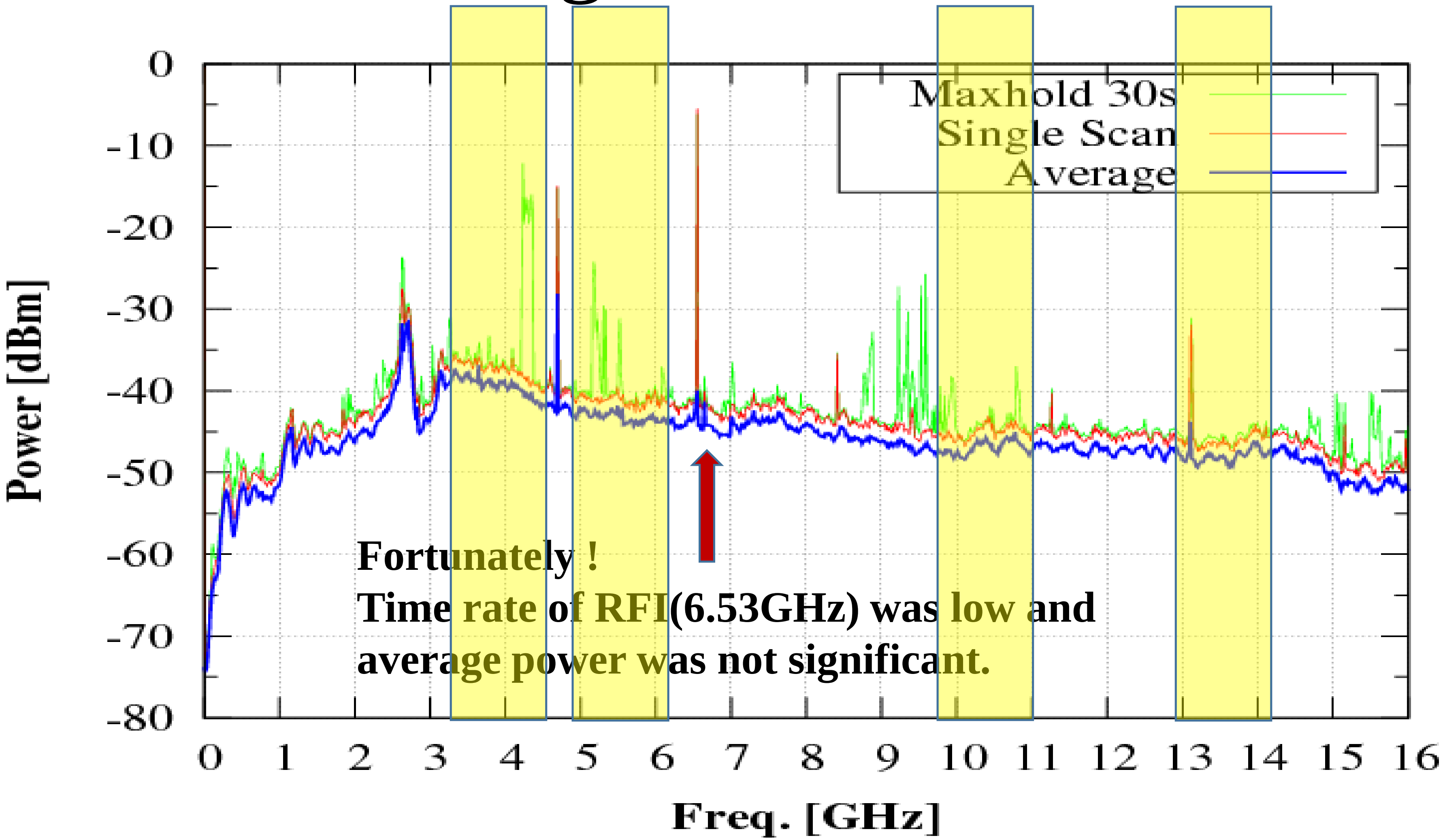
S1:System noise
S2: Radio source

It works under the condition [**Corr. Amp << 1**] and **each samples are independent each other.**



VLBI(1bit) is sampling the probability distribution of the signal.

Current State at Kashima 34m Broadband Signal



RBW=3MHz
Whole BW~12GHz

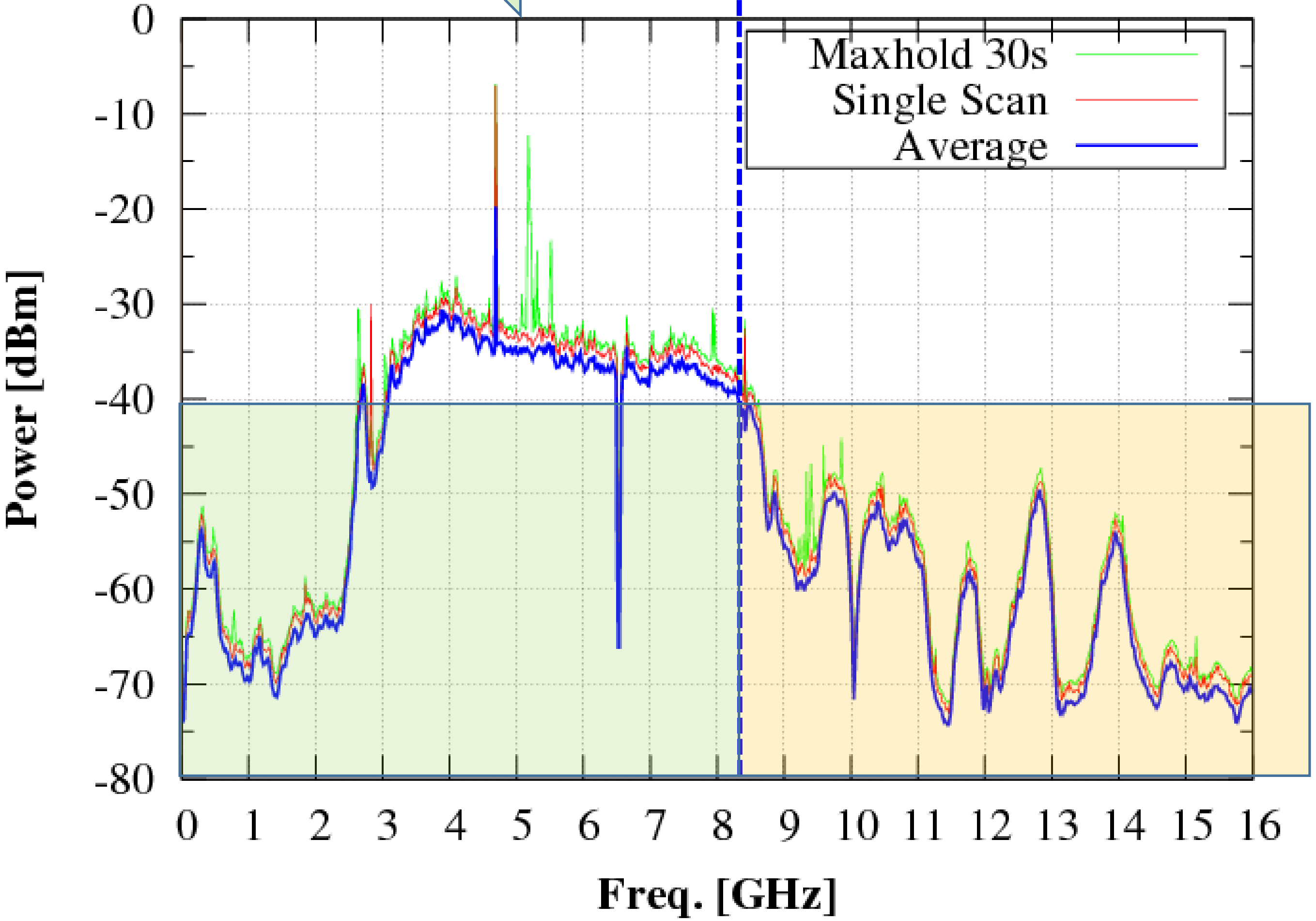
N=12GHz/3MHz
=36dB

Total Powe~-45+36
=-9dBm
< -5dBm (RFI)

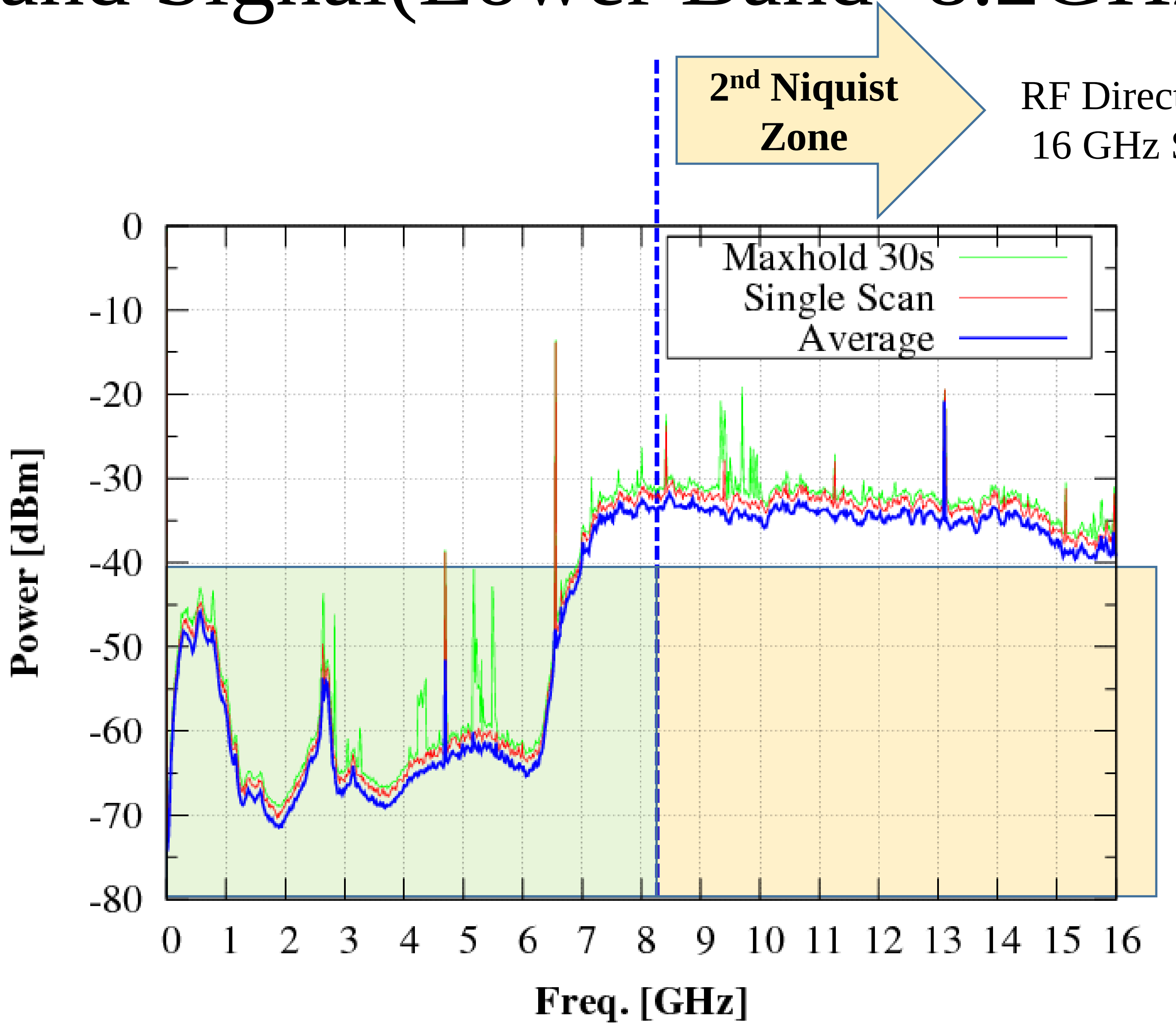
Real Input to A/D at Kashima 34m Broadband Signal(Lower Band<8.2GHz)

RF Direct
16 GHz Sampling

1st Niquist Zone



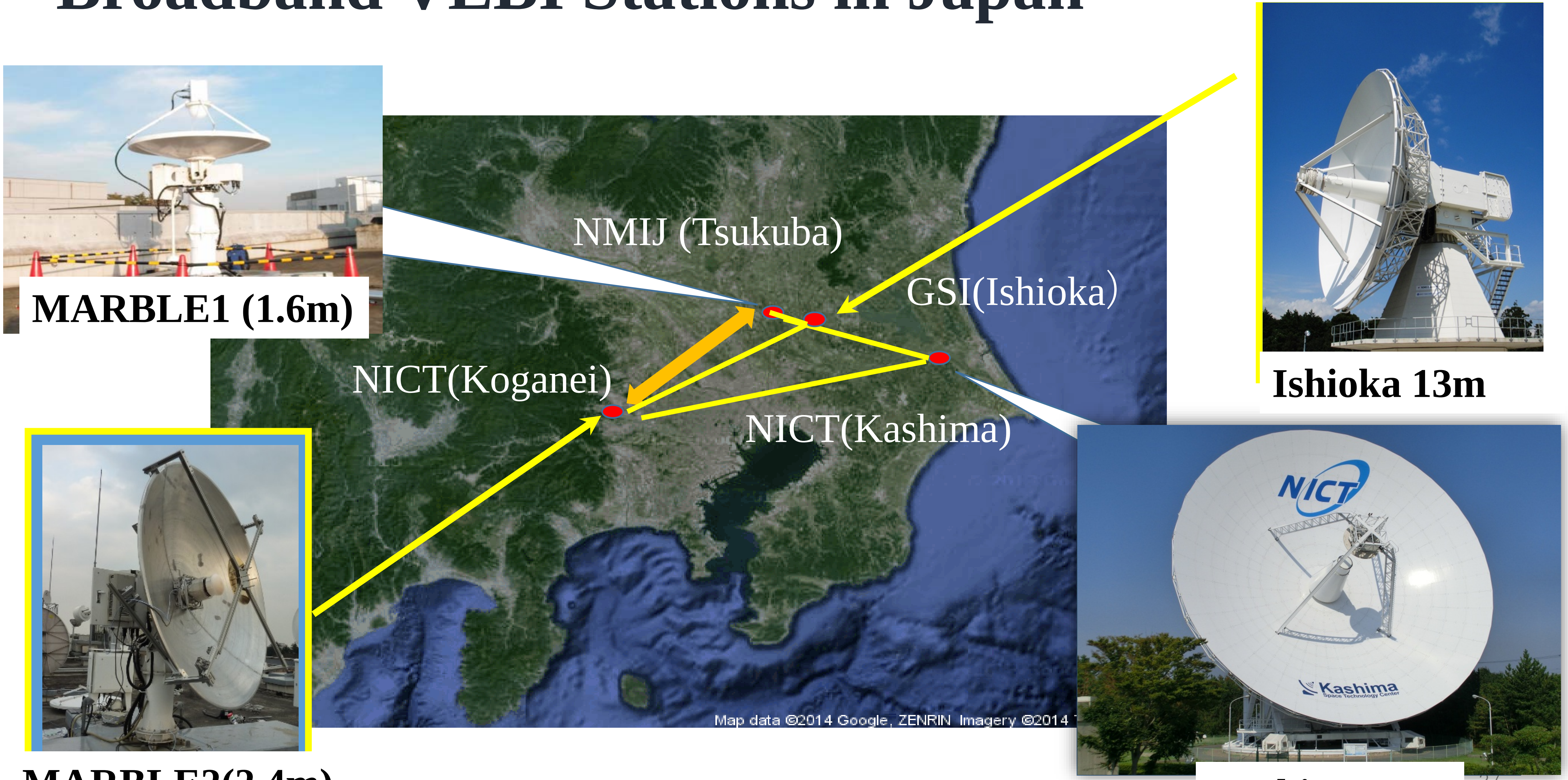
Real Input to A/D at Kashima 34m Broadband Signal(Lower Band>8.2GHz)



RF Direct
16 GHz Sampling

Broadband VLBI Experiments

Broadband VLBI Stations in Japan

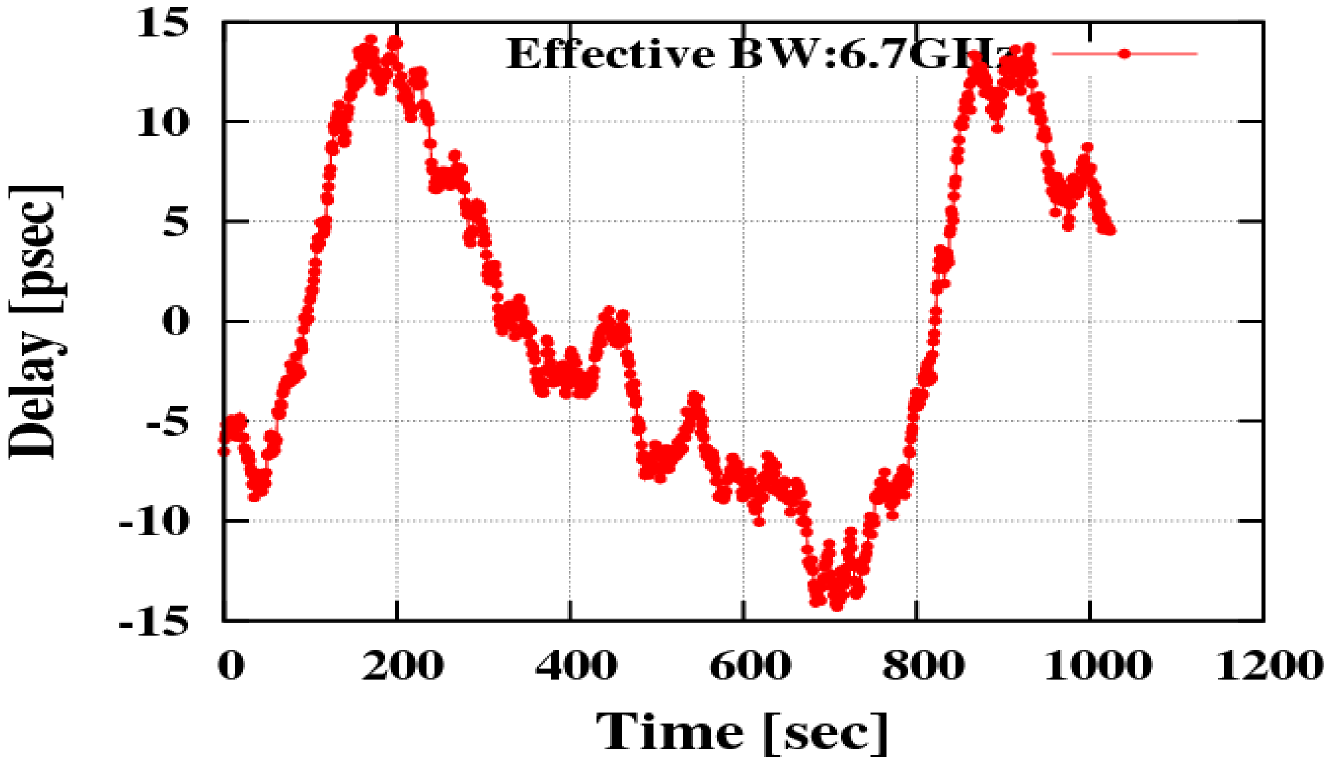


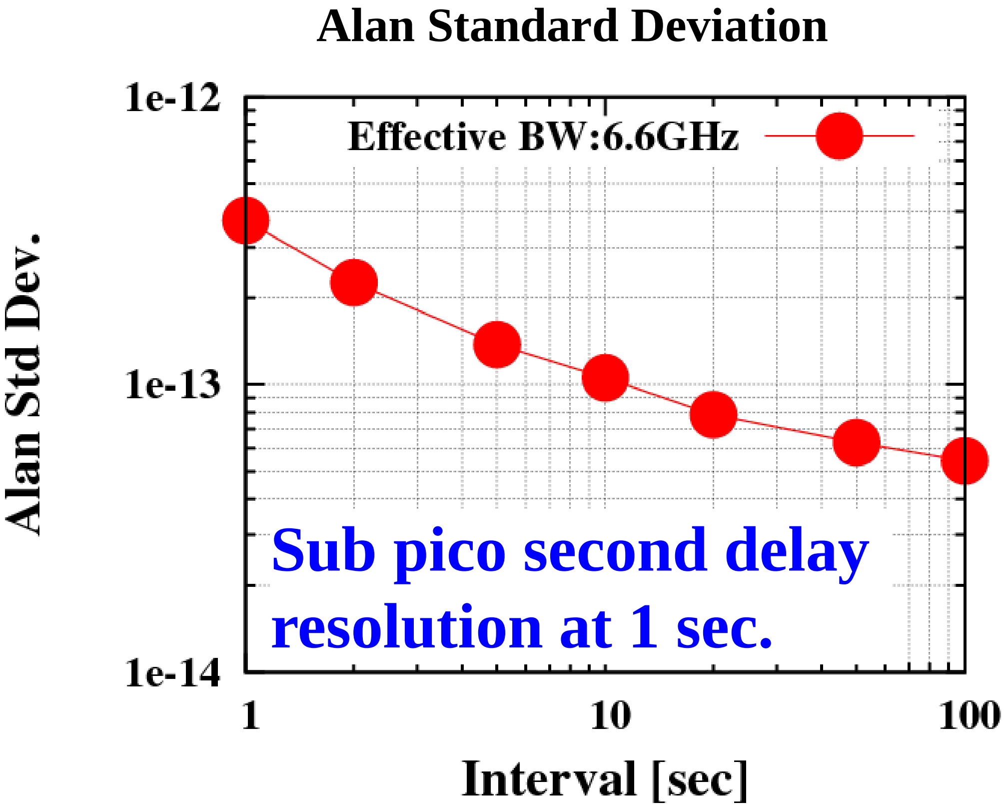
MARBLE2(2.4m)

Kashima 34m

Delay Behavior Broadband Delay (3.2-12.6GHz) Kashima34 – Ishioka 13m

Exp. on 14 Aug.2015,
Freq. array=(Lower Edge=3.2, 4.8, 8.8, 11.6GHz)



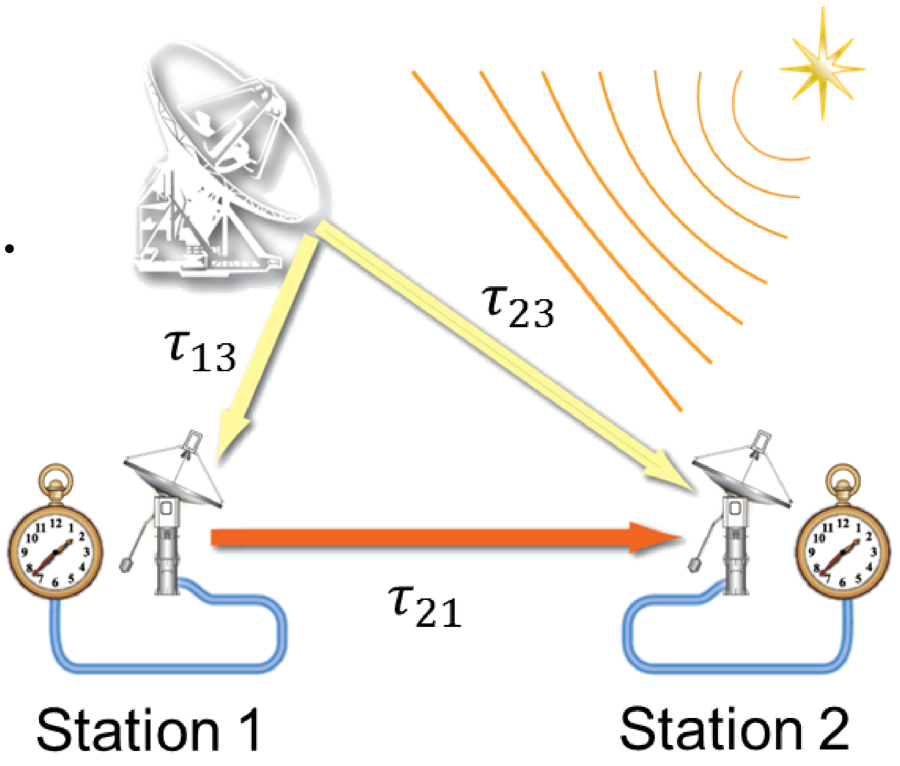


‘Small – Small’ Baseline

- Small diameter antenna is supposed to be tools for Atomic Clock comparison.
- Closure delay relation for ‘small-small’ baseline.

$$\tau_{21}(t_1) = \tau_{23}(t_1) - \tau_{21}(t_1) - \tau_{21}(t_1)\dot{\tau}_{23}$$

- Advantage:
  - Quick Slew and small distortion
  - Large Diameter’s effects are canceled out.
  - Lower Cost
- Disadvantage: Lower Sensitivity



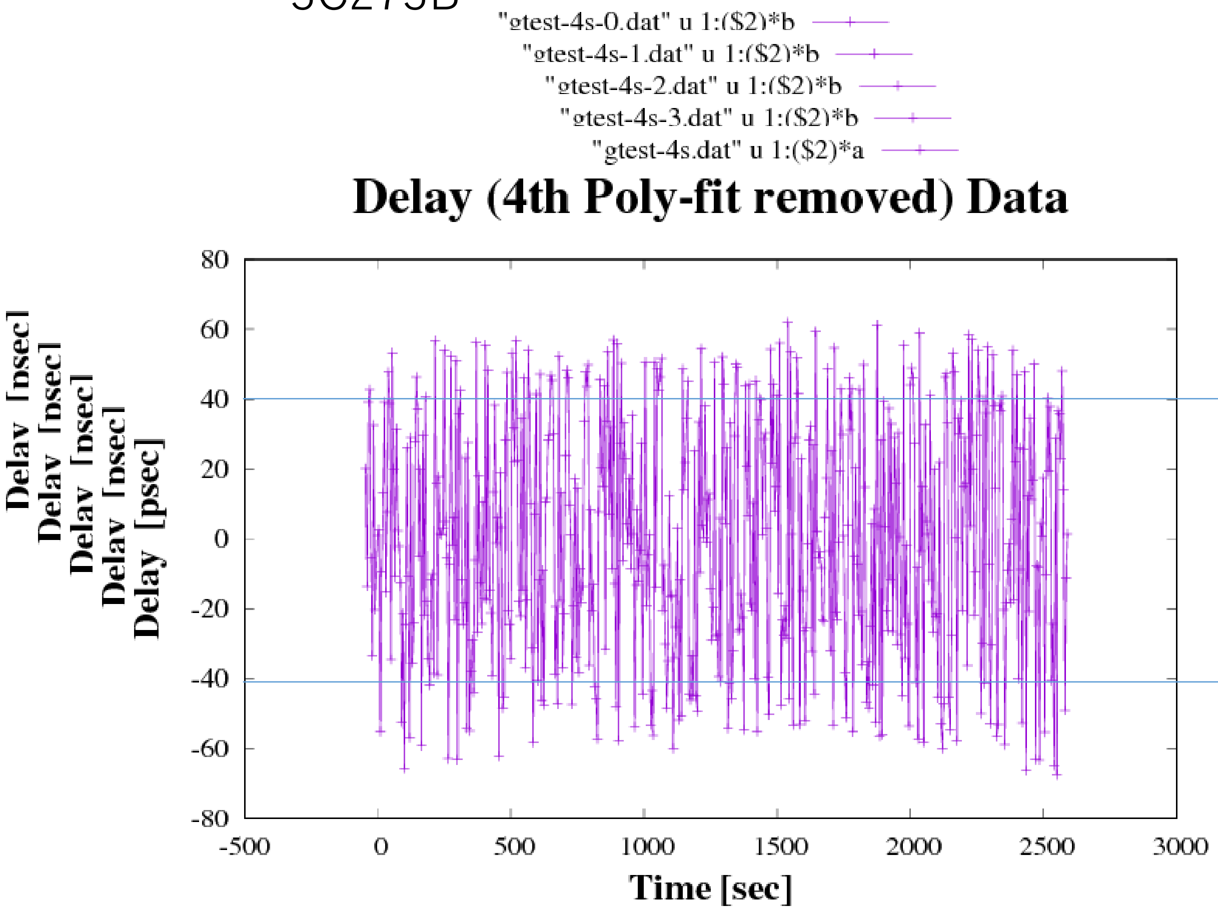
Delay Precision

Conventional

8180-8680MHz

S/X 500MHz

3C273B

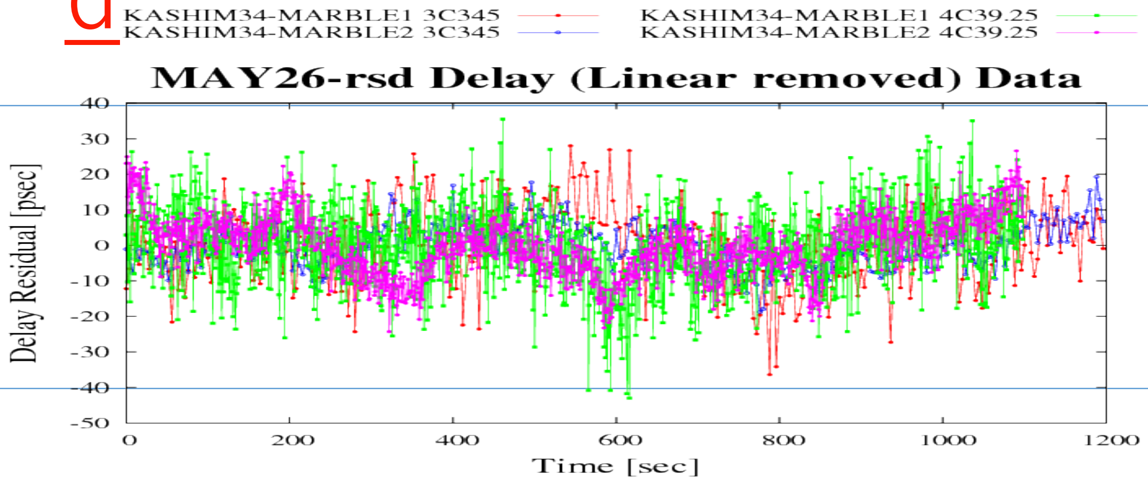


2.4m Diameter

1.6m Diameter

4C39.25

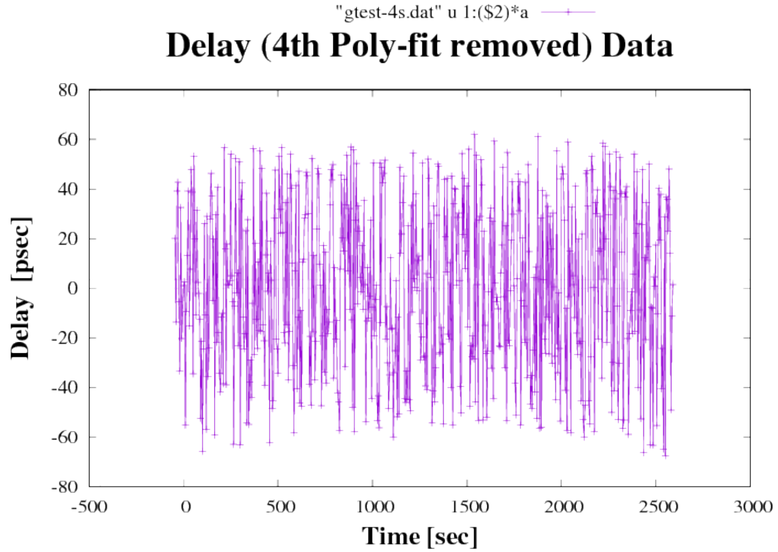
Broadband

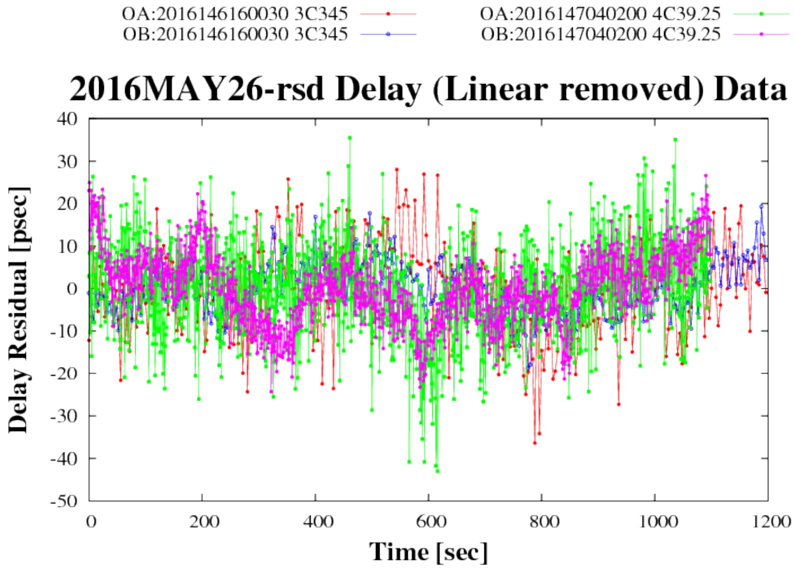


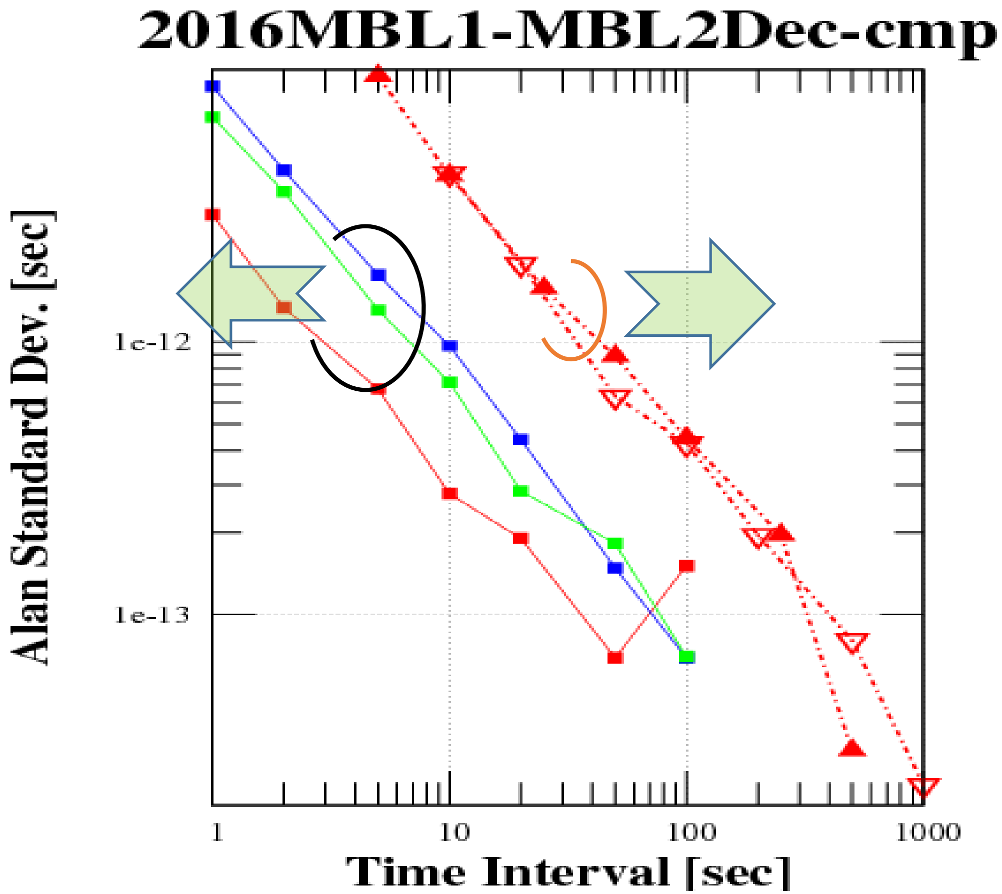
Conventional S/X Kas11 -Ko11 v.s. Broadband Mbl1(1.6m)-Mbl2(2.4m)

Exp. on 14 Aug.2015,

Freq. array=(Center Edge=3.8, 5.9, 8.7, 10.6 GHz)







Mbl1(1.6m)-Mbl2(2.4m)

Kas11(11m) - Kog11(11m

CALC/SOLVE Residual

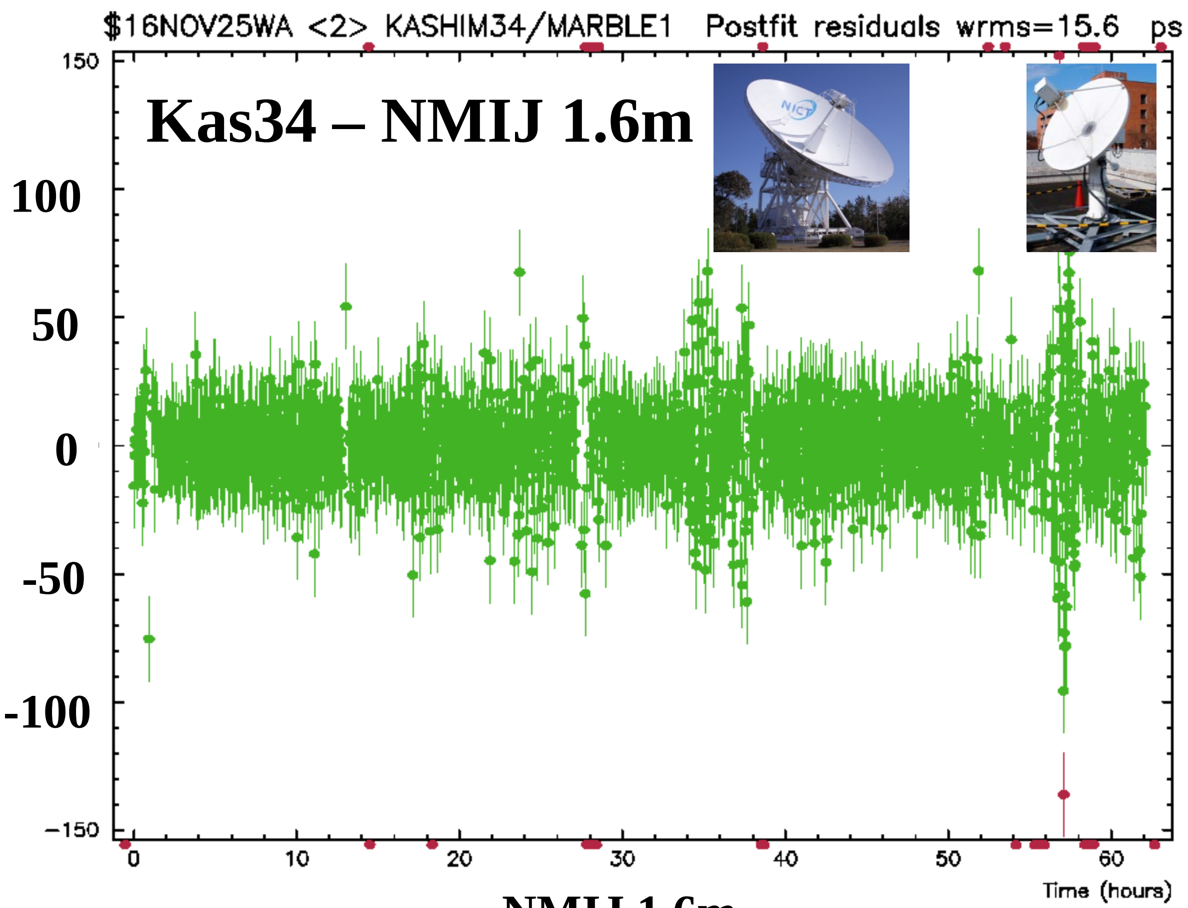
Baseline Length

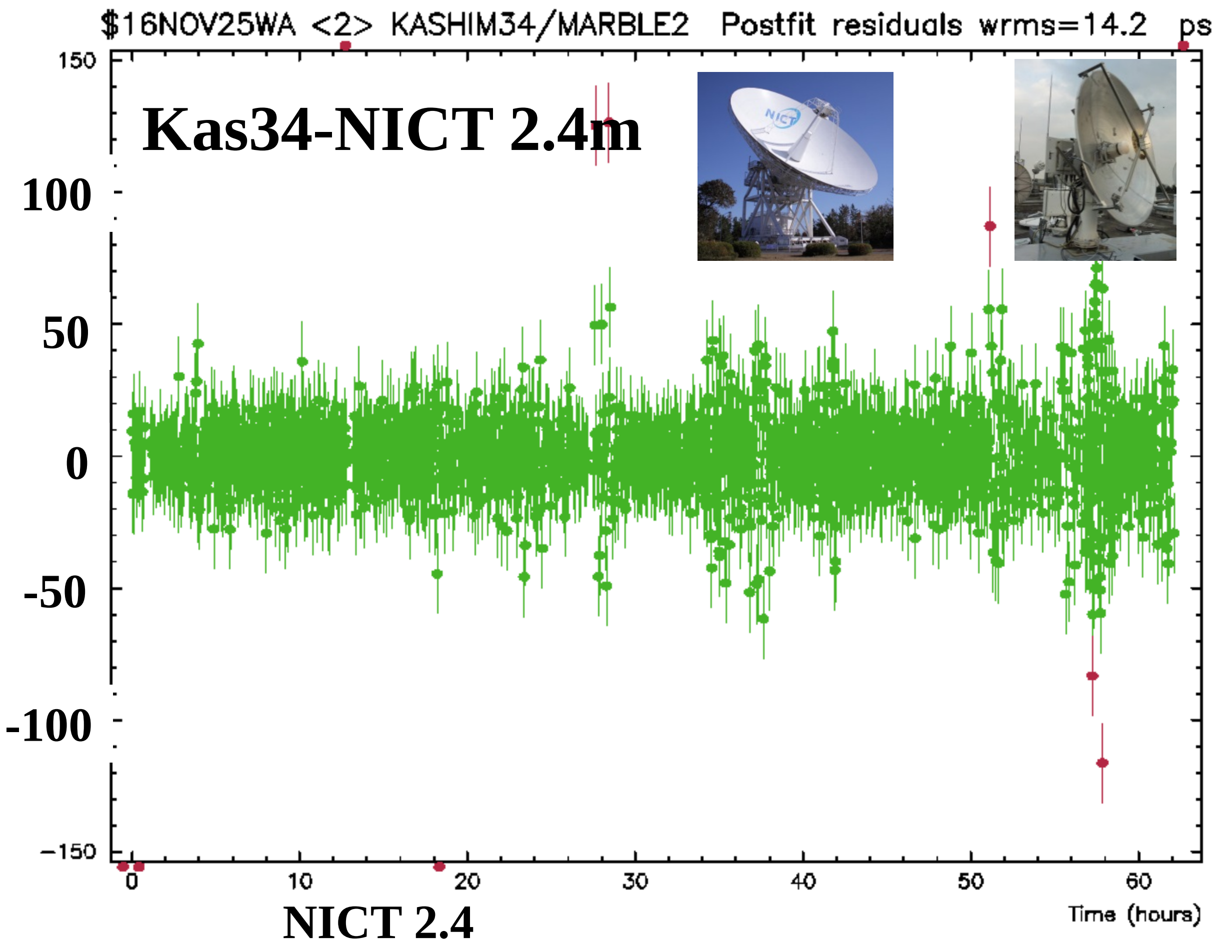
Kashim34 -NMIJ 1.6m : 48718193.8 mm 0.6 mm

Kashim34 - NICT 2.4m : 109427397.8 mm 0.7 mm

NICT 2.4m - NMIJ 1.6m : 70218038.2 mm 0.8 mm

WRMS Delay Residual ~ 16ps





NMIJ 1,6m

X : -3962279099.2 mm 1.9 mm

Y : 3308886482.2 mm 1.5 mm

Z : 3733538092.1 mm 1.8 mm

NICT 2.4

X: -3942068754.6 mm 1.8 mm

Y: 3368281011.8 mm 1.5 mm

Z: 3702003908.5 mm 1.7 mm

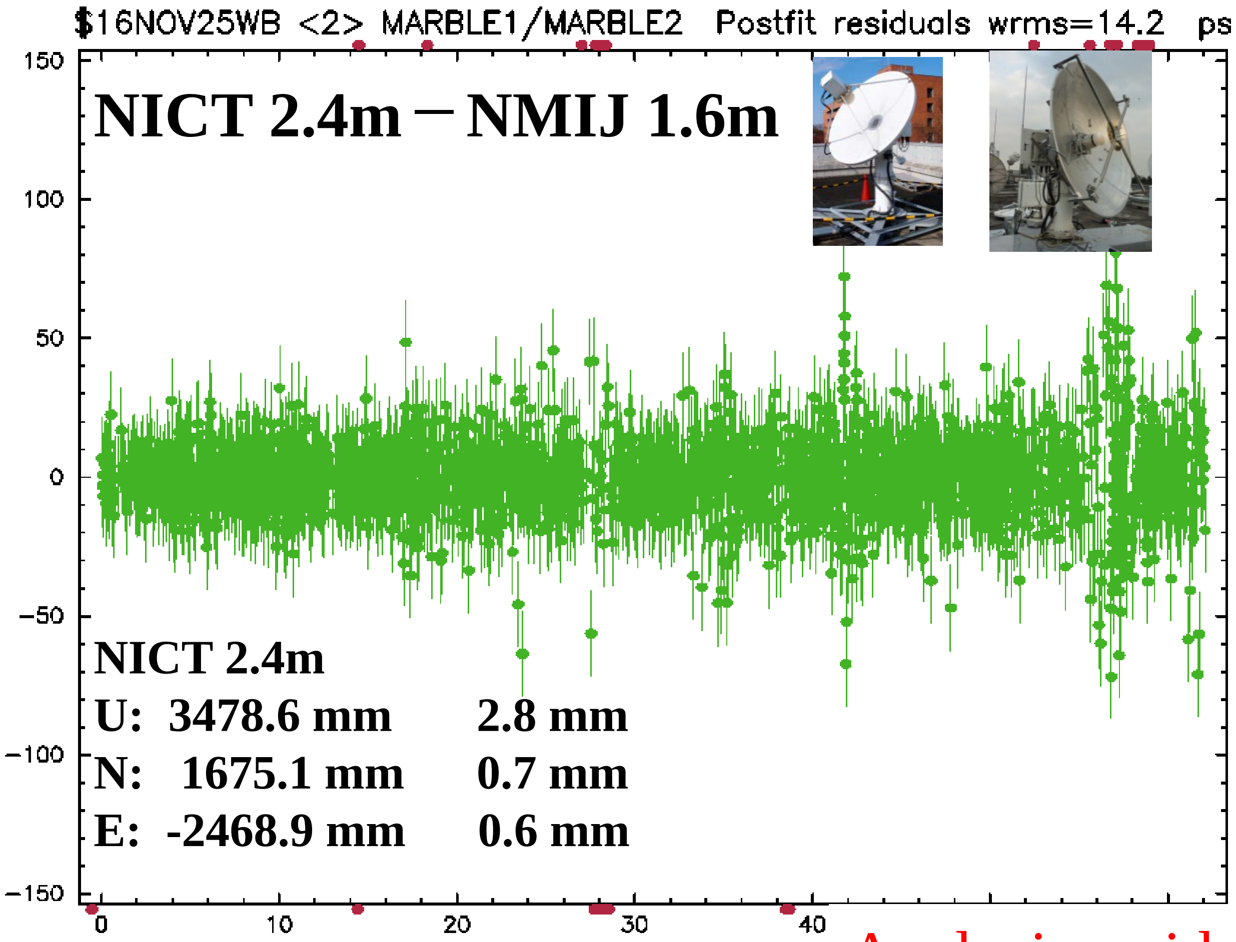
CALC/SOLVE Residual

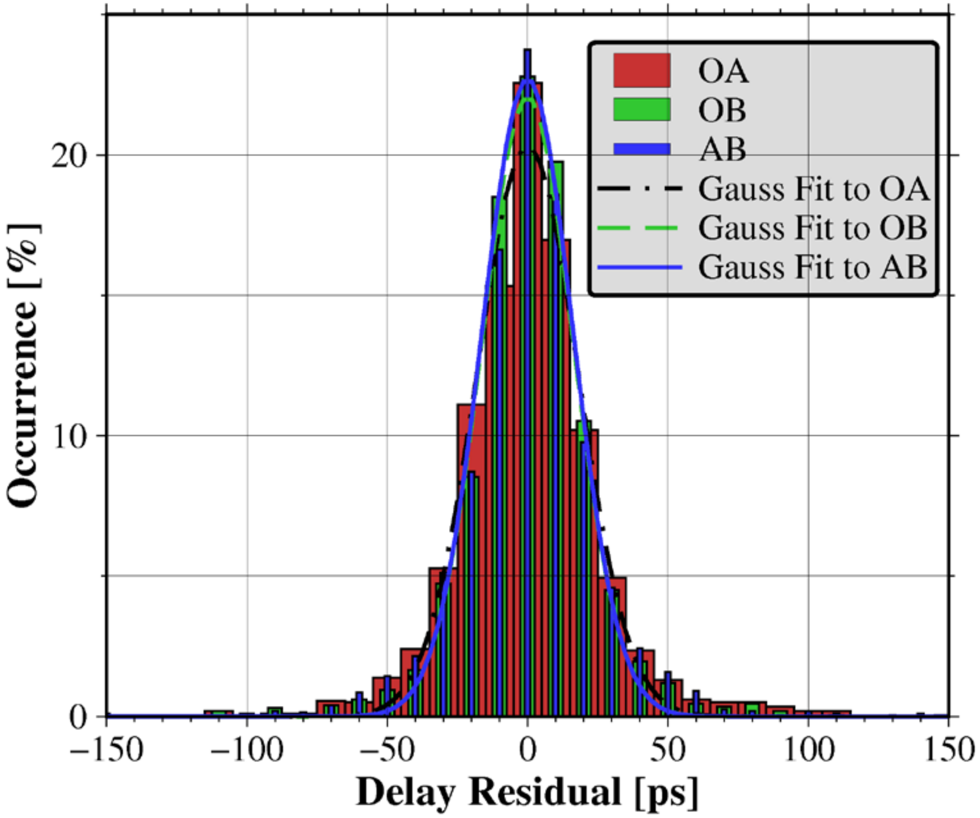
Baseline Length
MBL1(1.6m) – MBL2(2.4m): 70218041.2 mm 0.7 mm

$$\tau_{21}(t_1) = \tau_{23}(t_1) - \tau_{21}(t_1) - \tau_{21}(t_1)\dot{\tau}_{23}$$

O:Kashim34
A:MARBLE1 NMIJ 1.6m
B:MARBLE2 NICT 2.4m

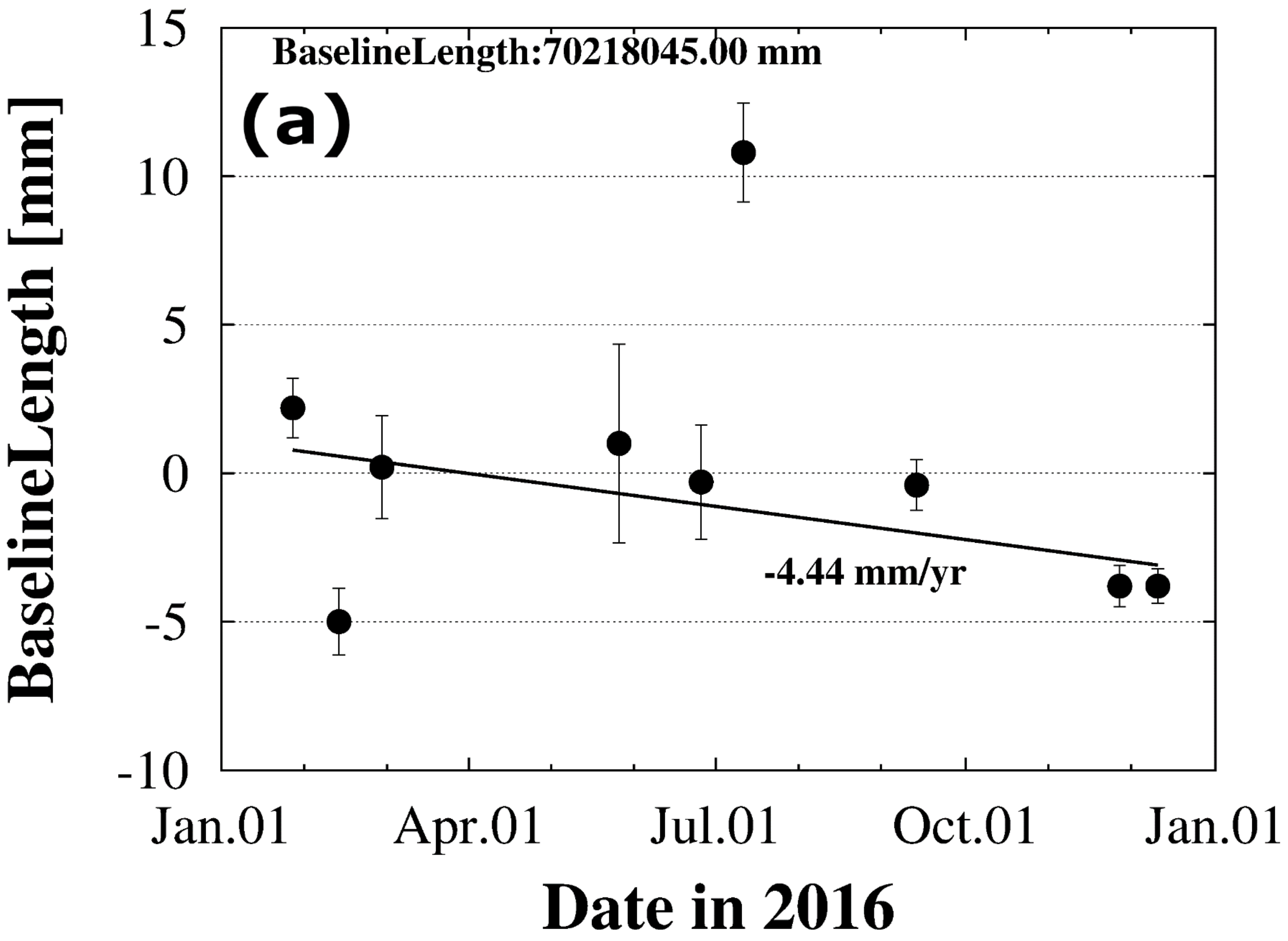
WRMS Delay Residual ~ 15 psec

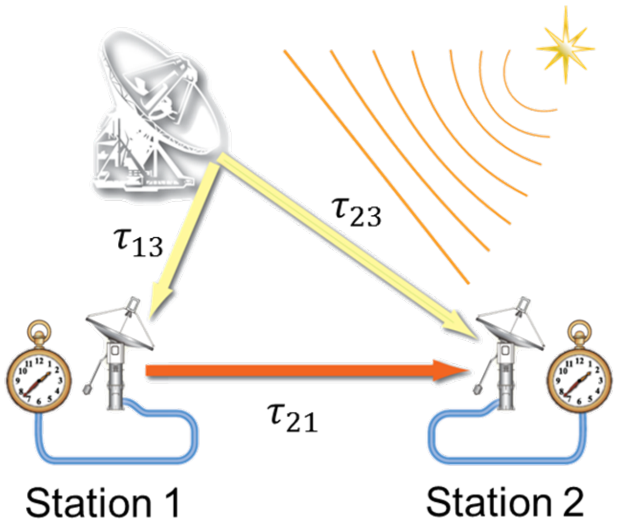




Analysis residual is dominated not by measurement precision, but unknown excess delay by troposphere.

Position Solution of MBL1-MBL2



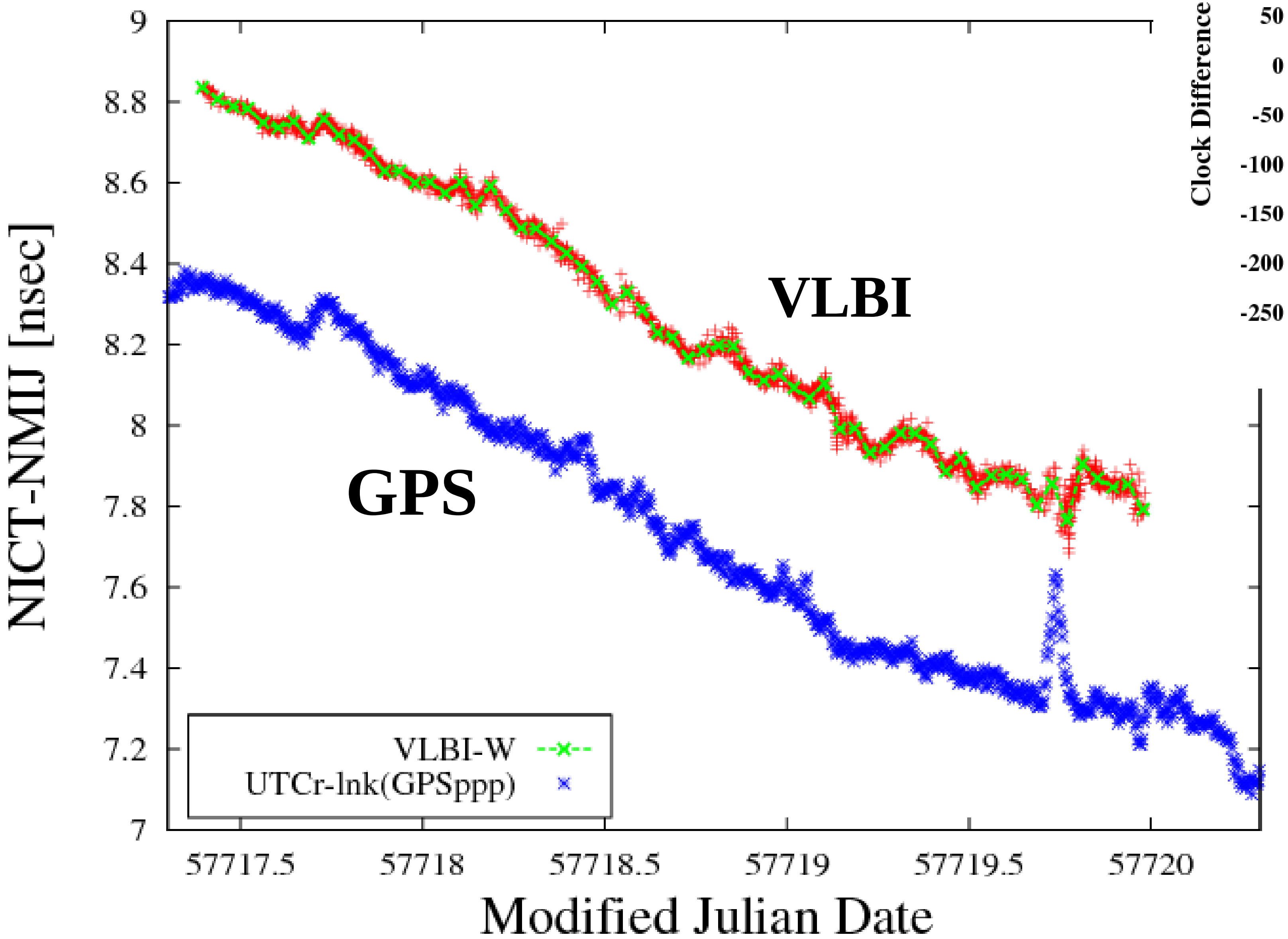


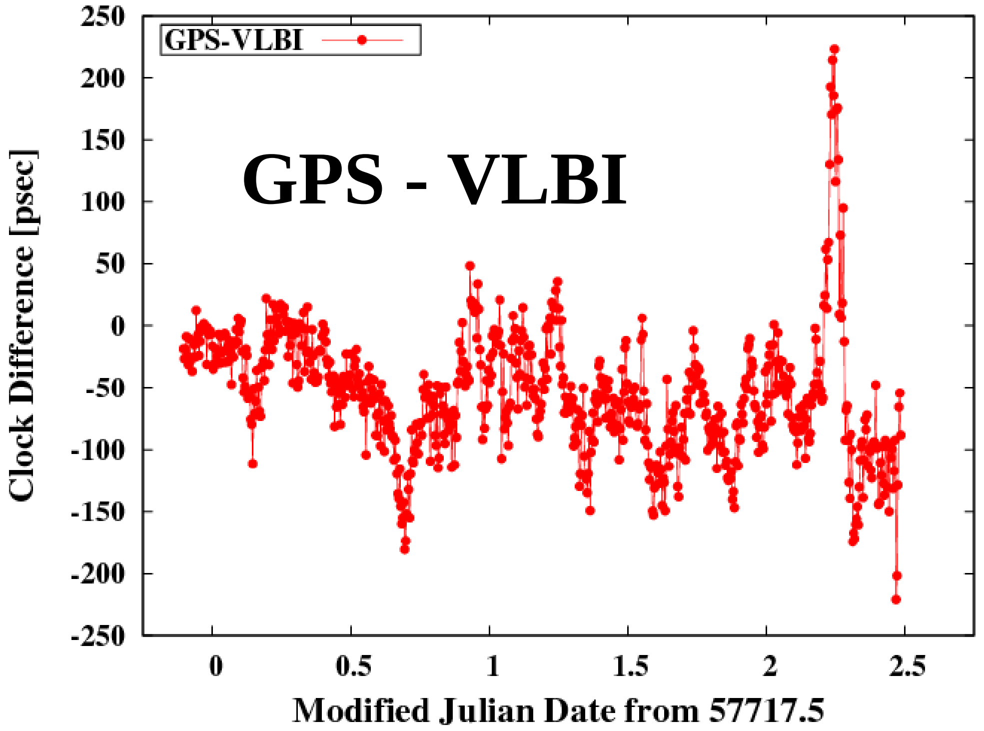
$$\tau_{21} = \tau_{13} - \tau_{23}$$

NICT 2.4m

NMIJ 1.6m

Clock Comparison via VLBI and GPS-ppp
2016Nov25 UTC(NICT) – UTC(NMIJ)



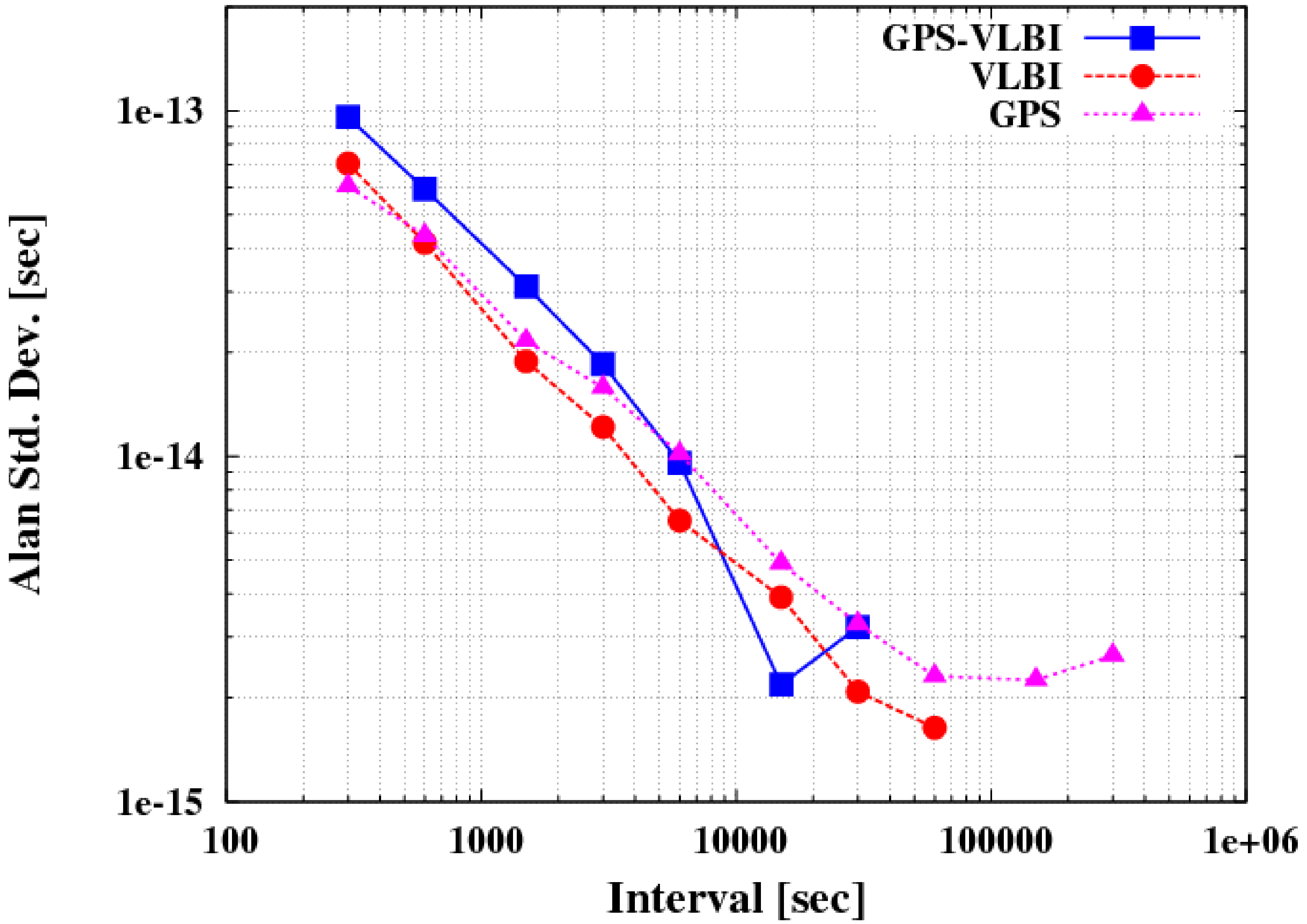


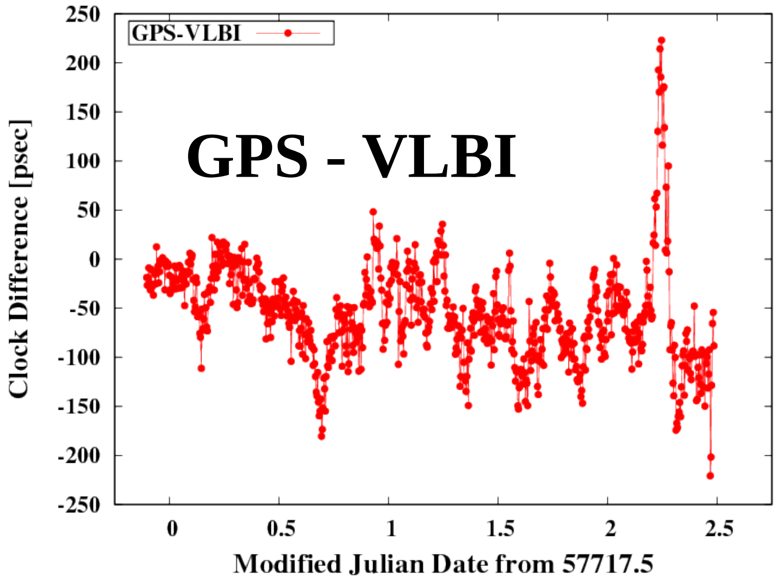
NICT 2.4m

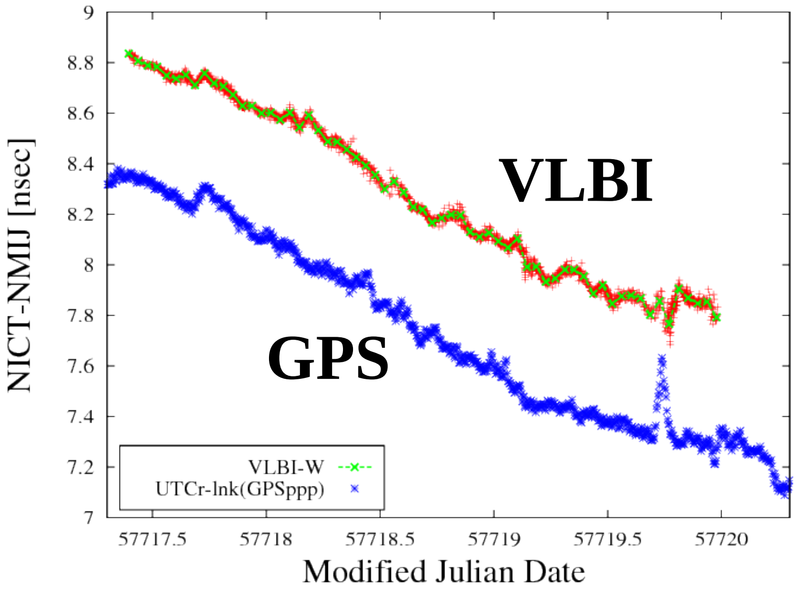
NMIJ 1.6m

Clock Comparison via VLBI and GPS

Allan STD of Clock by VLBI, GPS and GPS－VLBI.



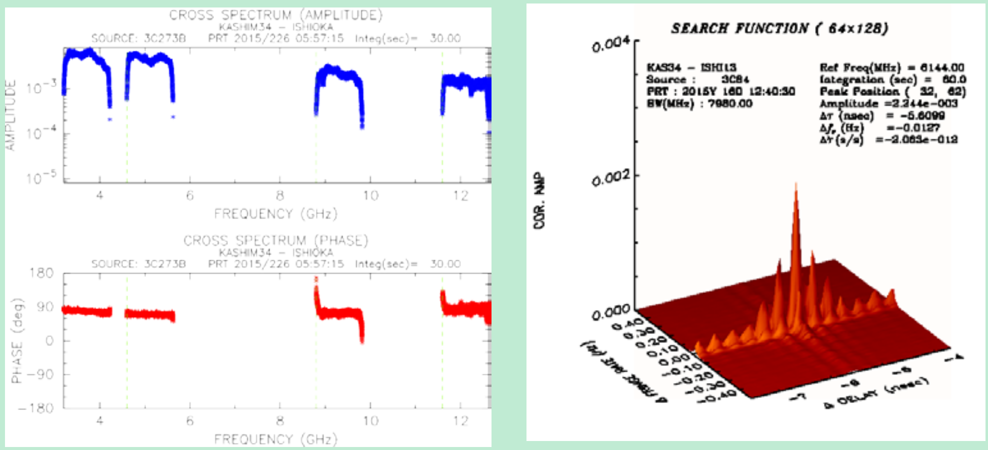




Summary

Broadband Feed: NINJA

RF-Direct Sampling K6/GALAS



Broadband bandwidth Synthesis

1. We developed Broadband VLBI Observation/Processing System
2. Broadband Observation is relatively robust to RFI.
3. Broadband (3-12GHz) observation gives higher precision delay measurement even with 1.6 m – 2.4m baseline.

Thank you for Attention

Acknowledgements

- Development of Broadband Feed was supported by a grant (2013-2014) of Joint Development Research from National Astronomical Observatory of Japan(NAOJ).
- Broadband experiments with Ishioka Station was kindly supported by GSI.
- Highs speed research network environment is supported by JGN.

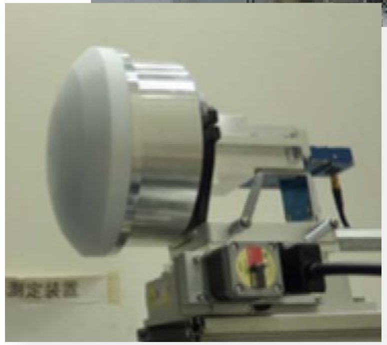
Current (April '07)Broadband Gala-V Project

Kashima 34m

Original broadband Feed
NINJA, IGUANA-H

MARBLE1 2.4m
@NMIJ(Tsukuba)

MARBLE12 2.4m
@Konganei



NINJA Feed
For Marble