Broadband VLBI with transportable small station for geodesy and frequency transfer

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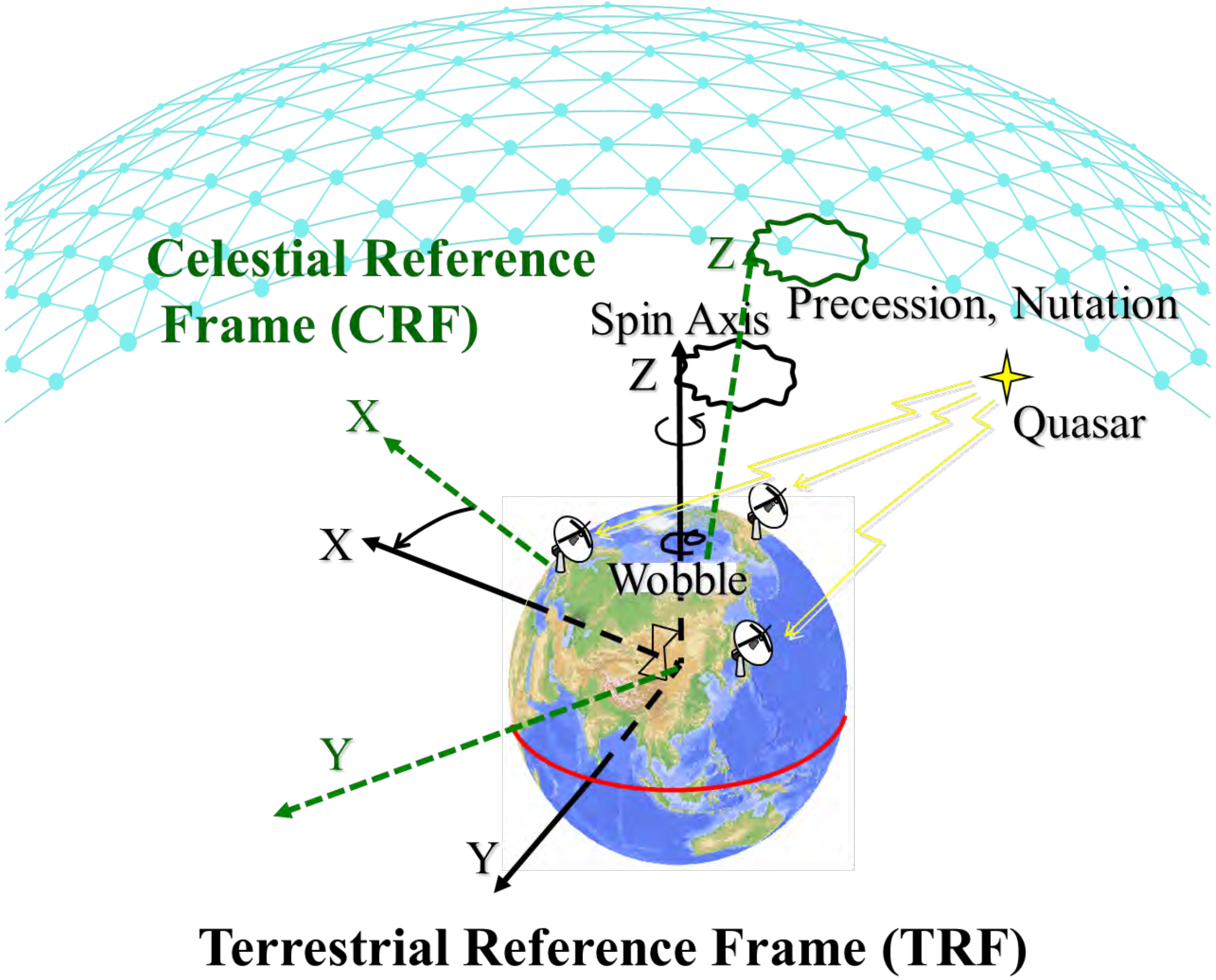
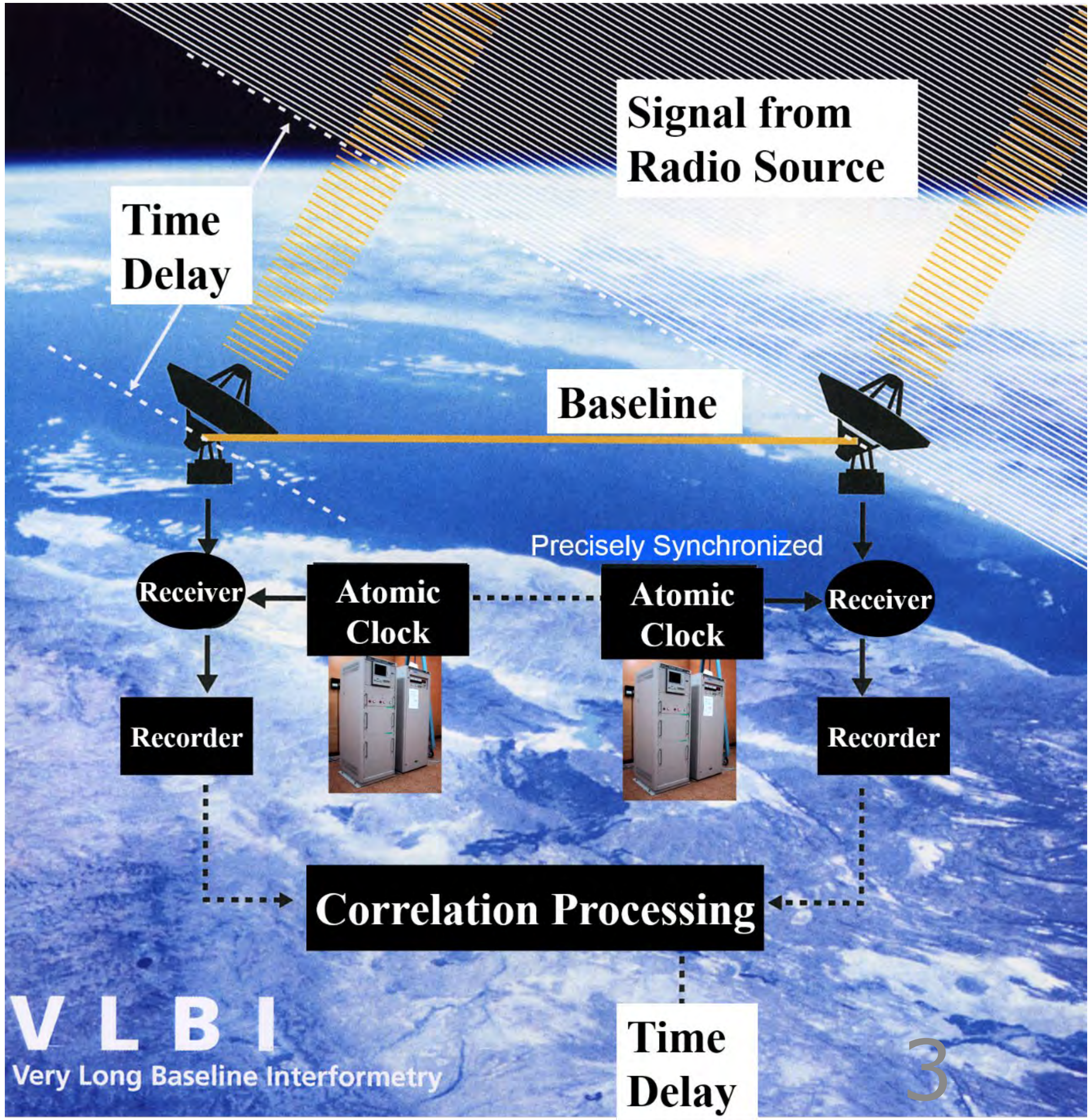
NICT
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
BIPM

Contents

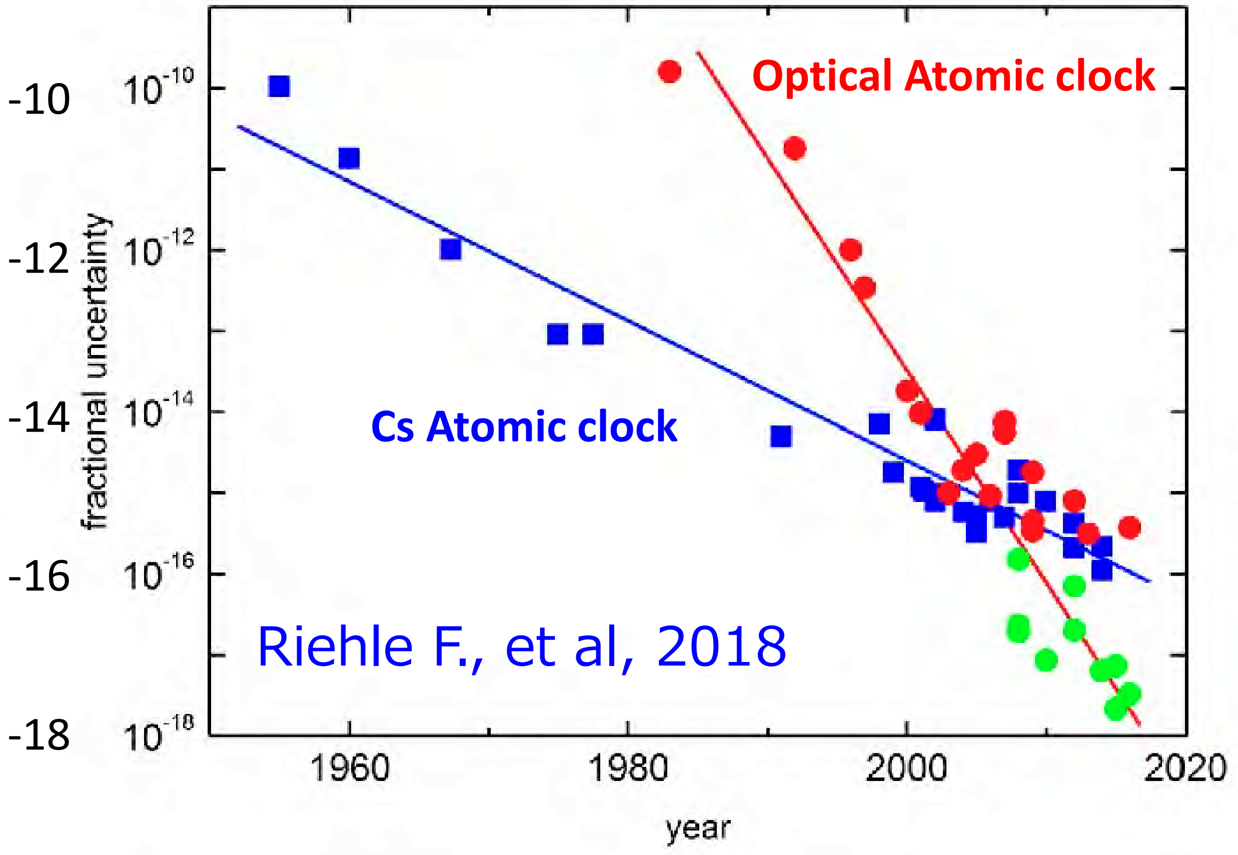
1. Introduction (VLBI, Optical Frq. Std.)
2. Technical aspect of broadband VLBI System
3. Frequency transfer experiments: INRiM(IT)–NICT(JP)
4. Error source and subject of further research.

VLBI(Very Long Baseline Interferometry)





Rapid progress of Optical Atomic Freq. Std.



- Uncertainty of optical frequency standards reached in the order of 10^{-18}
- Atomic clock of 9 species are candidates traceable to SI second.

econdary Representations of the second

Table 2. SRS as of 2017.

Frequency (Hz)	Fractional uncertainty	Transition
6834 682 610.904 3126	6×10^{-16}	^{87}Rb ground state hfs
429 228 004 229 873.0	4×10^{-16}	^{87}Sr neutral atom, $5s^2\ ^1S_0$–$5s5p\ ^3P_0$
444 779 044 095 486.5	1.5×10^{-15}	$^{88}Sr^+$ ion, $5s\ ^2S_{1/2}$–$4d\ ^2D_{5/2}$
518 295 836 590 863.6	5×10^{-16}	^{171}Yb neutral atom, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$
642 121 496 772 645.0	6×10^{-16}	$^{171}Yb^+$ ion, $^2S_{1/2}$–$^2F_{7/2}$
688 358 979 309 308.3	6×10^{-16}	$^{171}Yb^+$ ion, $6s\ ^2S_{1/2}$–$5d\ ^2D_{3/2}$
1064 721 609 899 145.3	1.9×10^{-15}	$^{199}Hg^+$ ion, $5d^{10}6s\ ^2S_{1/2}$–$5d^96s^2\ ^2D_{5/2}$
1121 015 393 207 857.3	1.9×10^{-15}	$^{27}Al^+$ ion, $3s^2\ ^1S_0$–$3s3p\ ^3P_0$
1128 575 290 808 154.4	5×10^{-16}	^{199}Hg neutral atom, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$

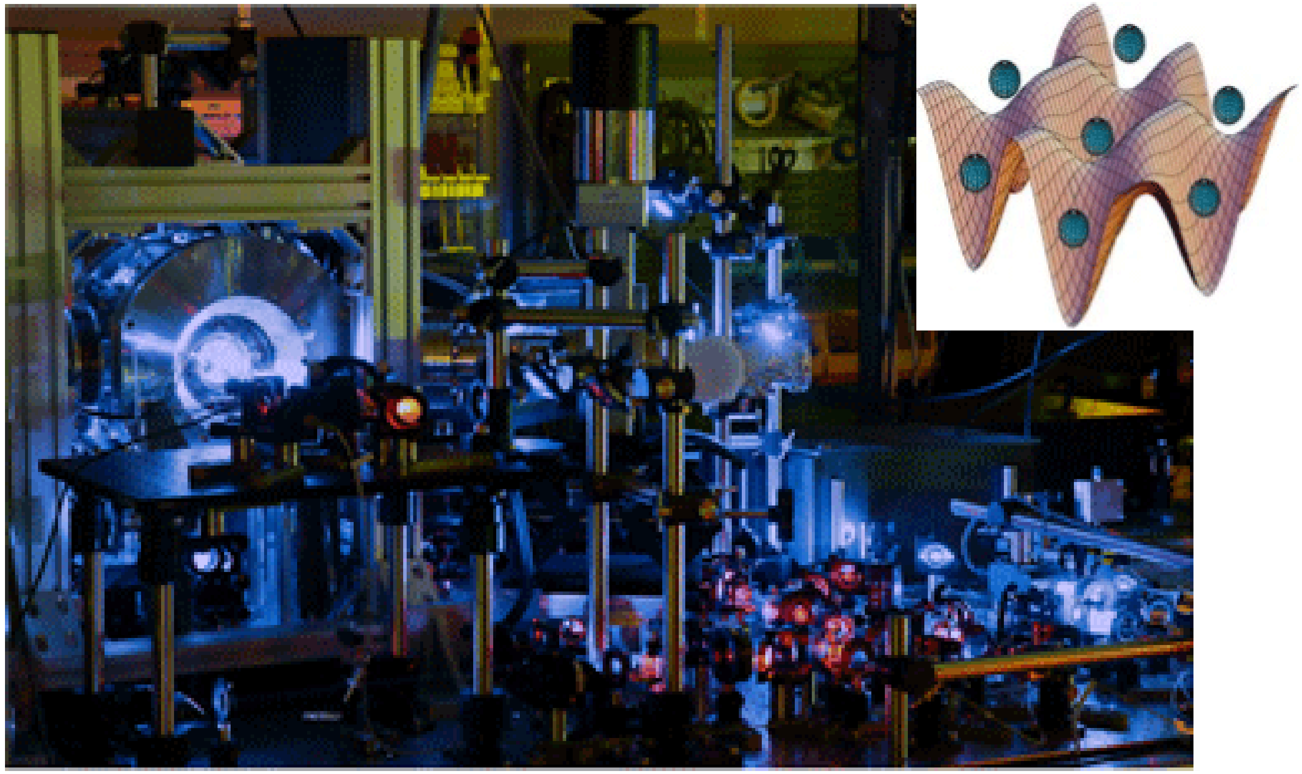
Riehle F., et al, 2018

Frequency standards

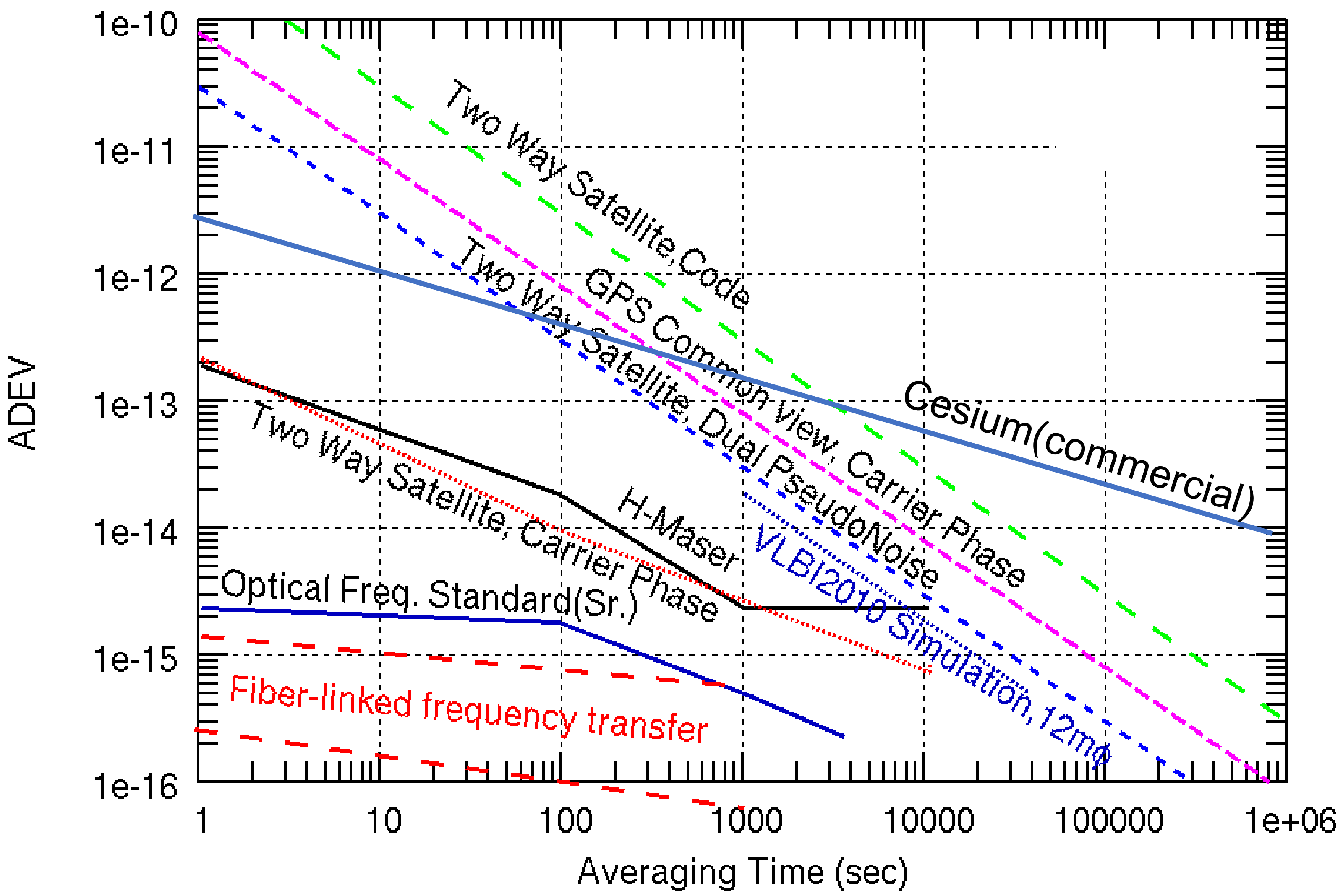
Cs Clock

H-maser

Strontium Optical lattice clock

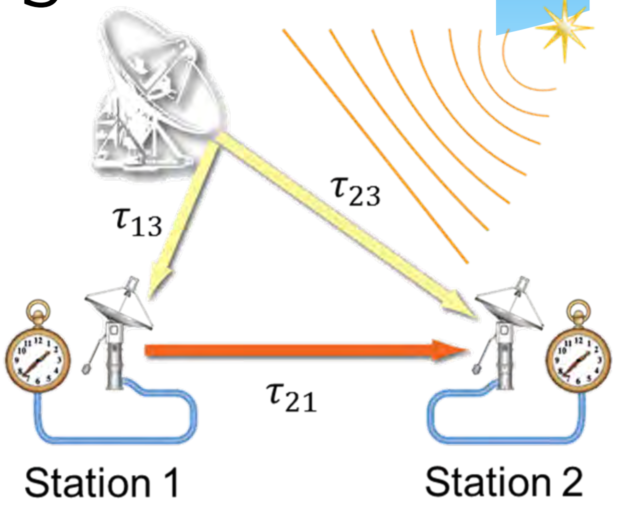


Typical stability of clock and comparison techniques

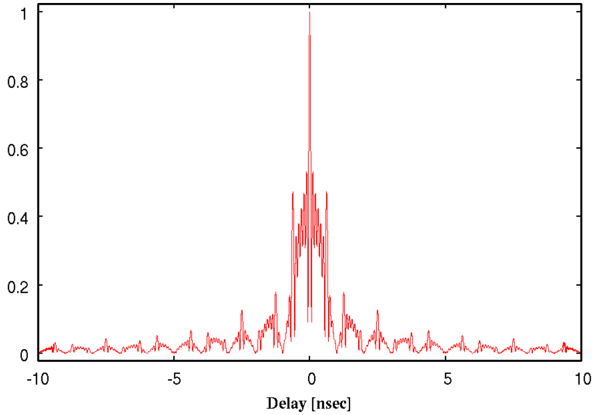


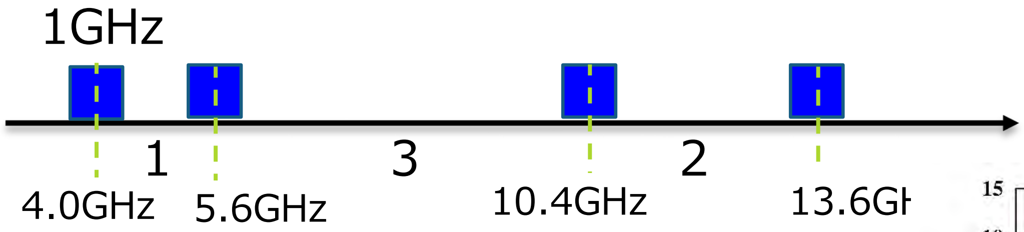
Overview of the Project

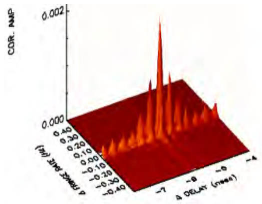
- **Objective :** Intercontinental precise Clock comparison with transportable Broadband antenna.   SNR～ D1 x D2 x S
- **Feature : Broadband VLBI compatible with VGOS**
  - Key technologies
    - Broadband feed
    - RF Direct Sampling
    - Broadband bandwidth synthesis
  - Data acquisition:1024MHz width 4 bands in 3-14GHz
    - Frequency array: 4.0GHz, 5.6GHz, 10.5GHz,13.6GHz
    - Effective bandwidth: 3.8GHz (10 times wider than conventional S/X)



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

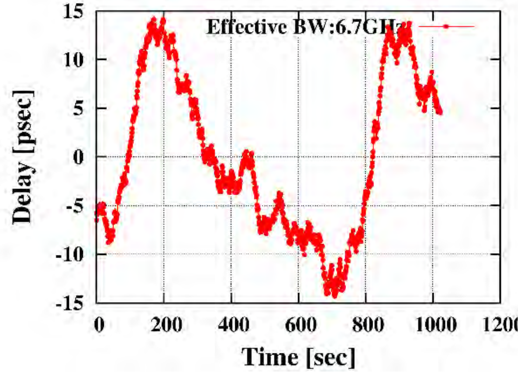


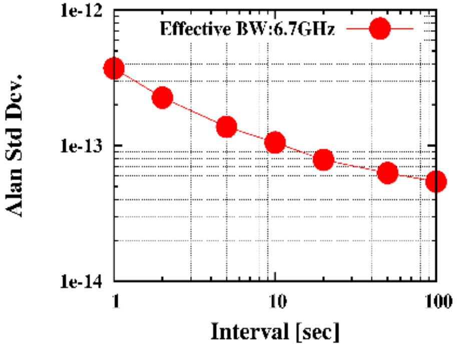




Delay resolution function

10 times better delay resolution



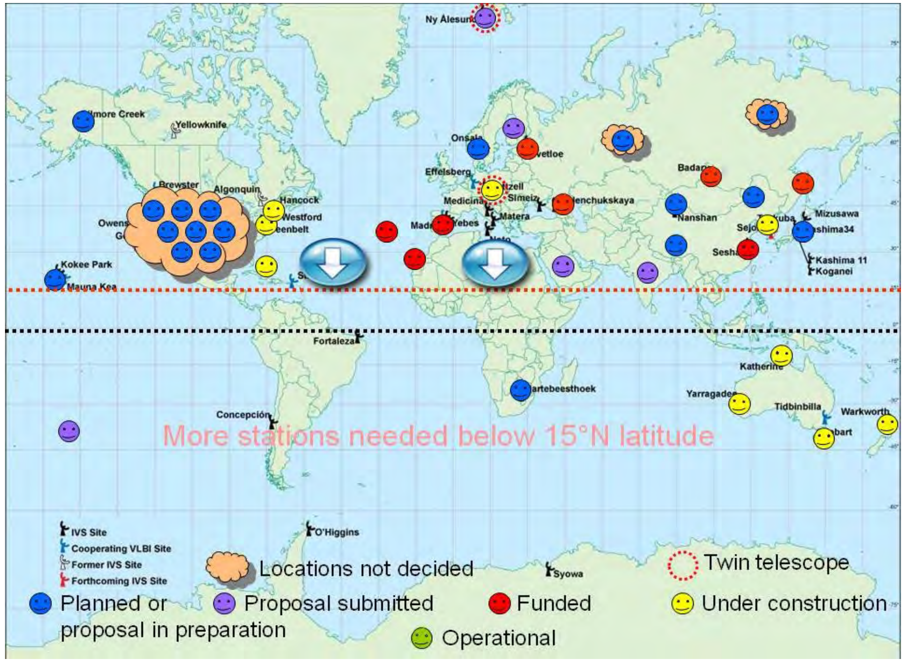


VGOS(VLBI Global Observing System) for geodesy

- VGOS: A new VLBI system promoted by the IVS

  (International VLBI Service for Geodesy and Astrometry)

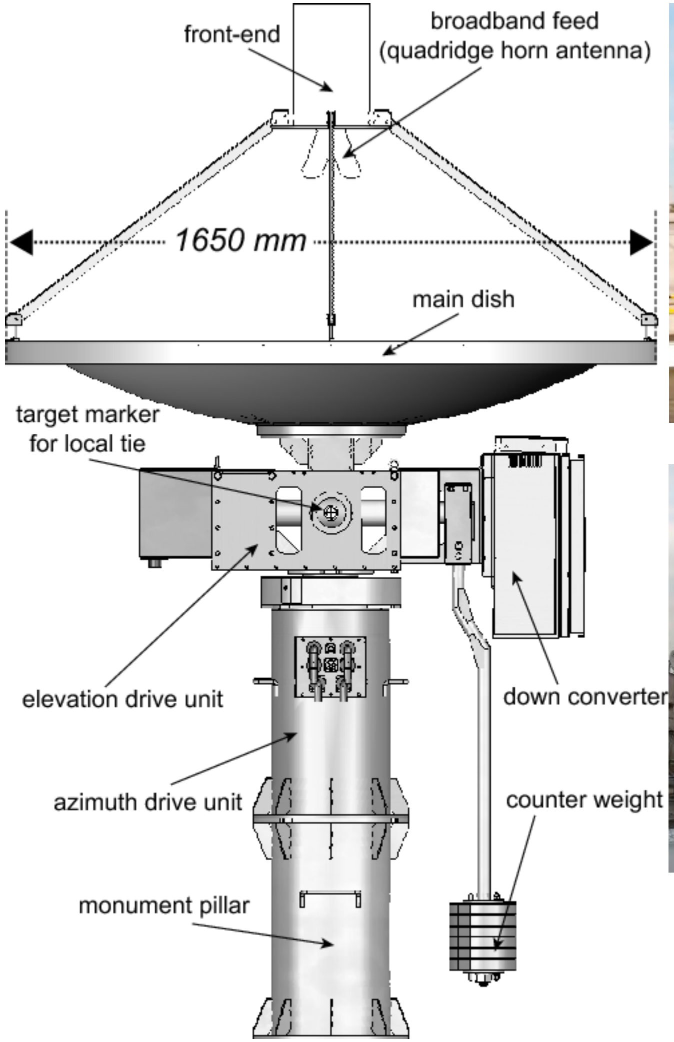
  - Frequency Range : 2-14 GHz → one order higher precision delay
  - Fast Slew Antenna: 12 deg./sec → Better Atmosphere calibration
  - Targeting 1mm position accuracy.



Ishioka 13m diameter antenna (GSI Japan)

Observation System

Small VLBI Antenna



2.4m diameter

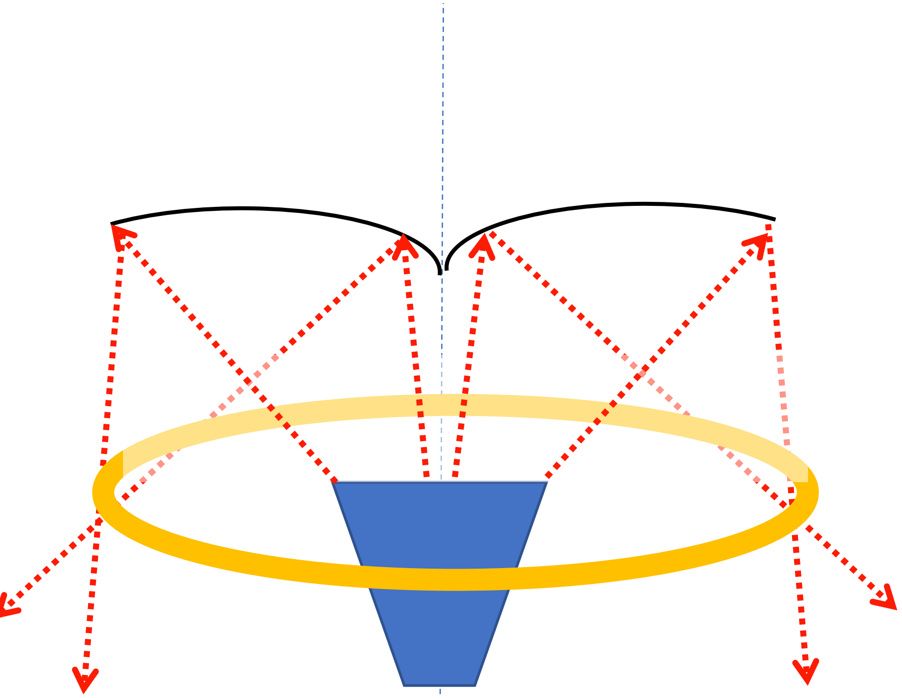
16Gsps Sampler

Broadband Receiver

Reason why NICT Developed own Broadband Feeds

Ujihara et al.(2018)
https://doi.org/10.1007/1345_2018_41

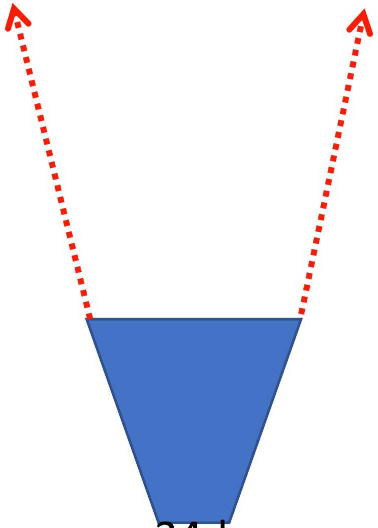
Requirement of
Broadband Frequency and
Narrow beam width



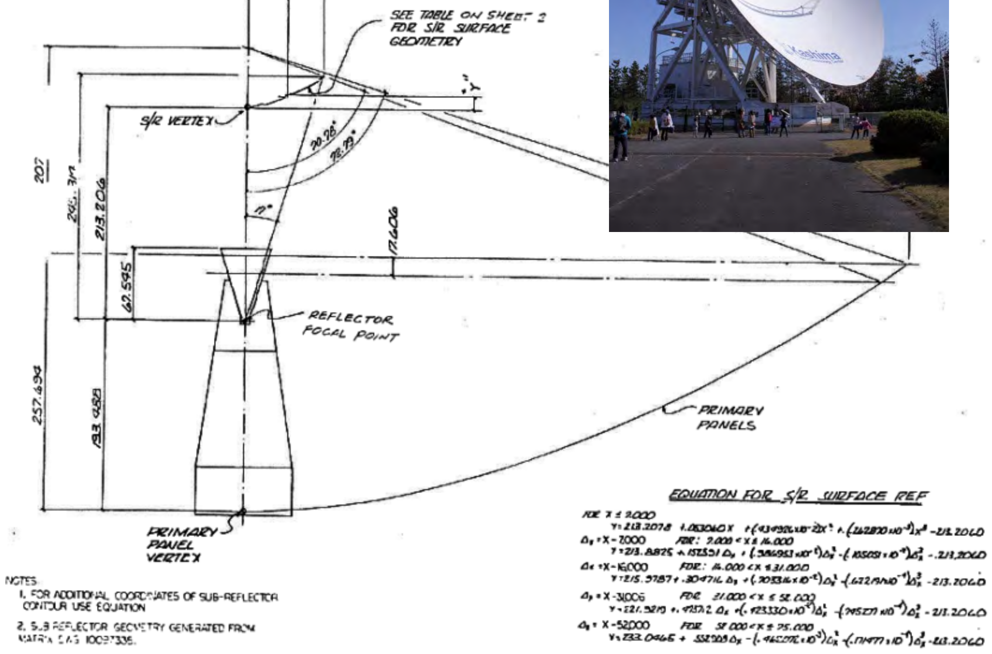
～120deg.

Eleven Feed

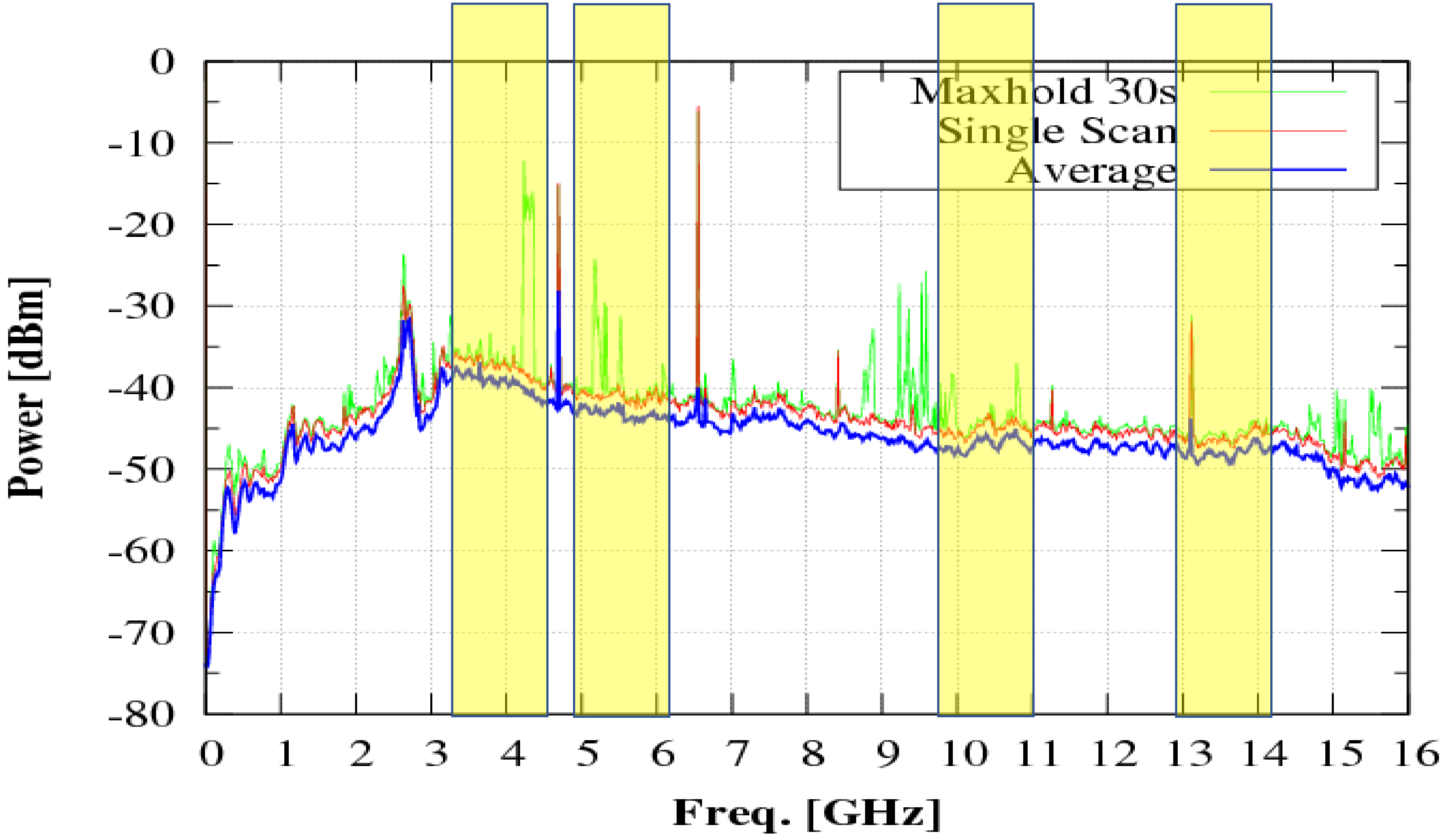
QRFH



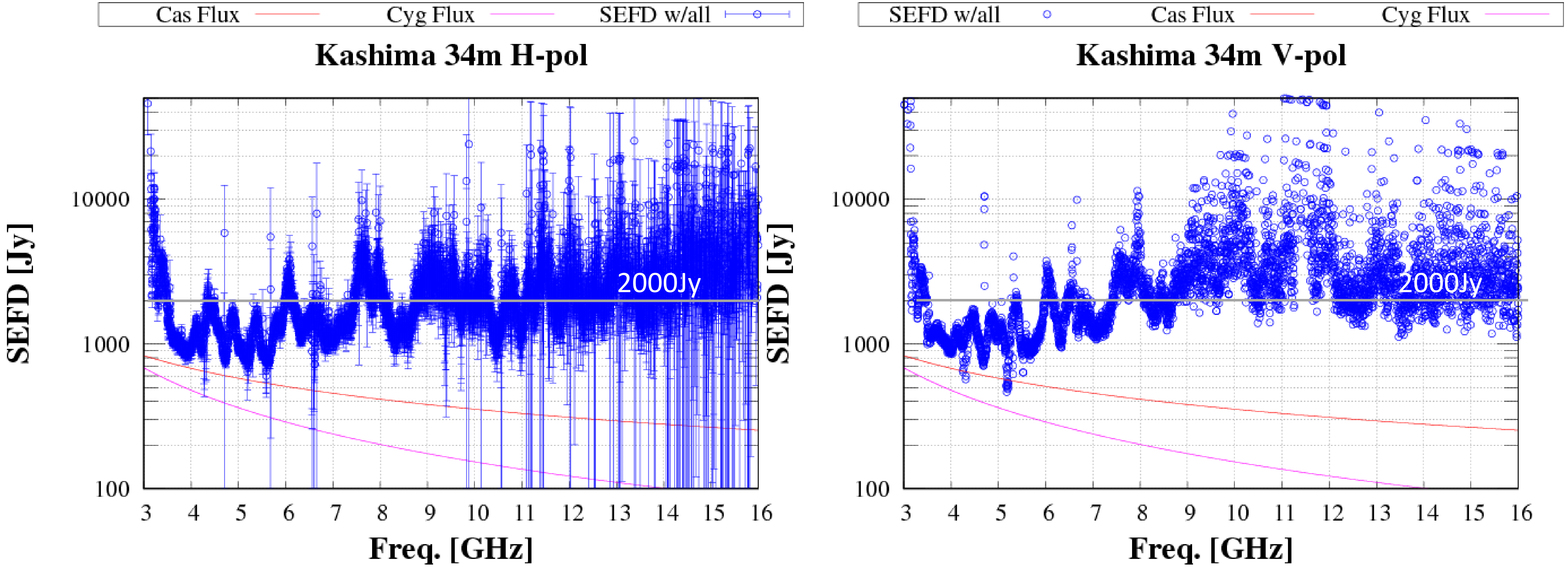
～34deg.



鹿島34m広帯域アンテナ受信信号　スペクトル



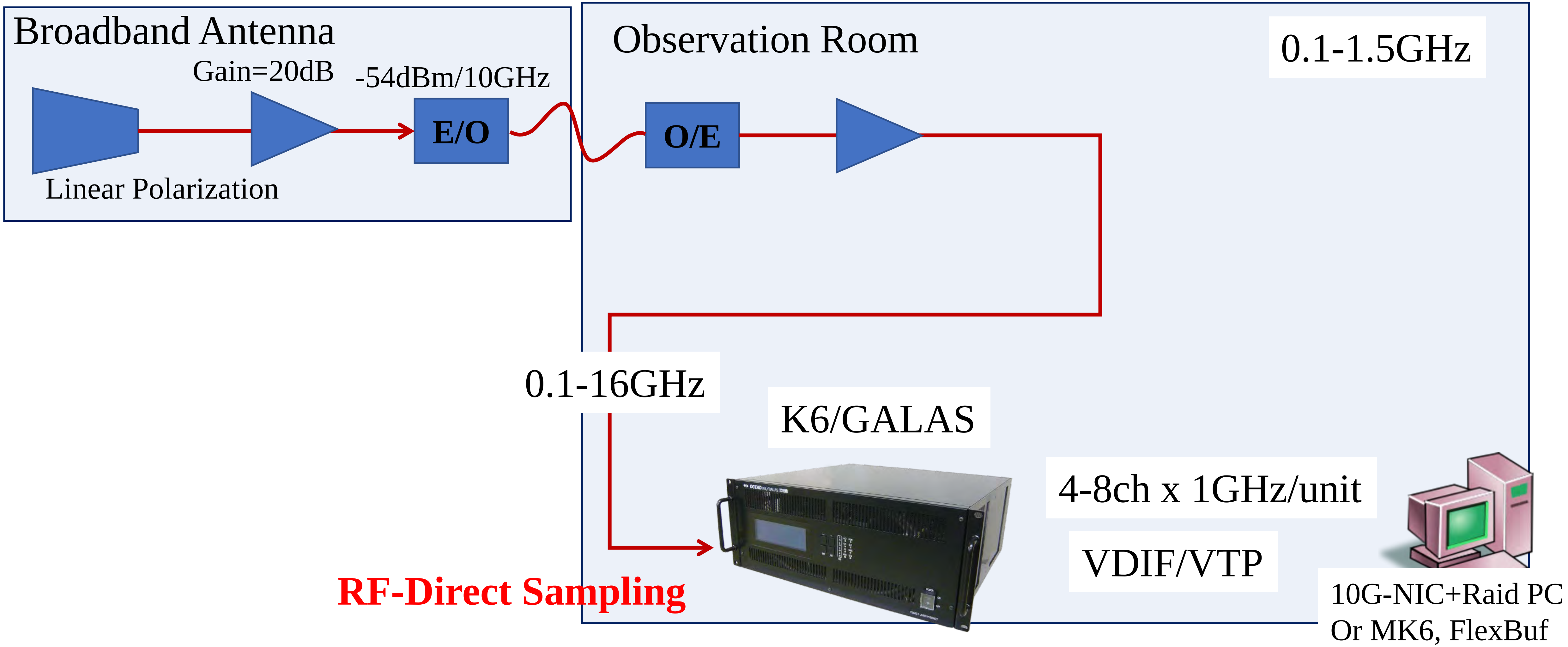
System equivalent flux density (SEFD) of Kas34



Data Acquisition System

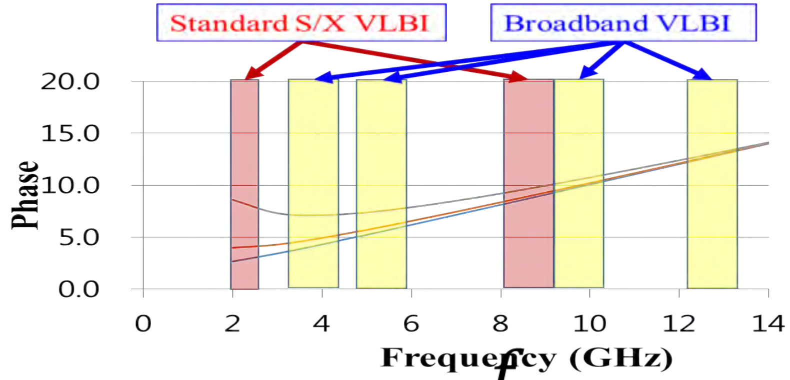
300kelvin = -174 dBm/Hz
-74dBm/10GHz

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

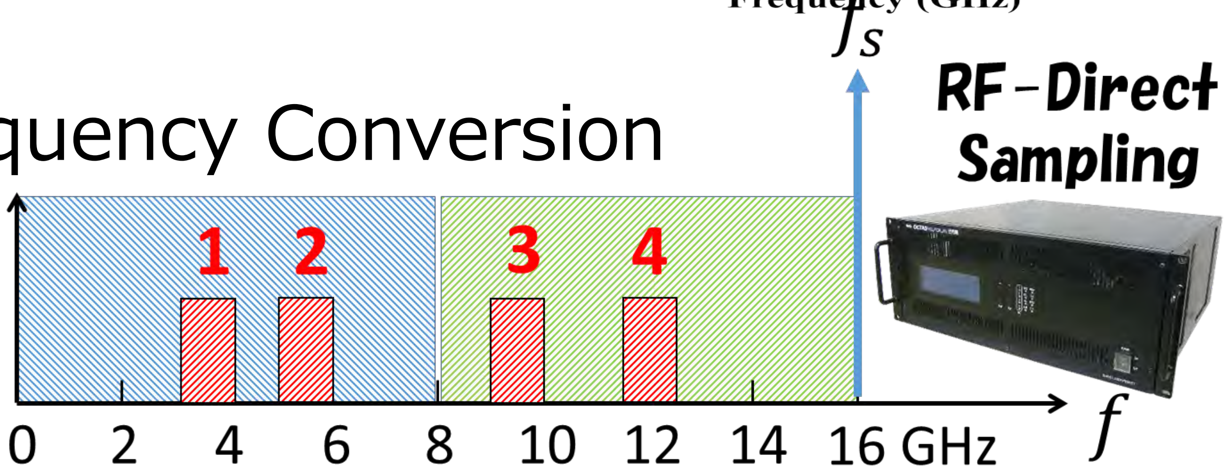


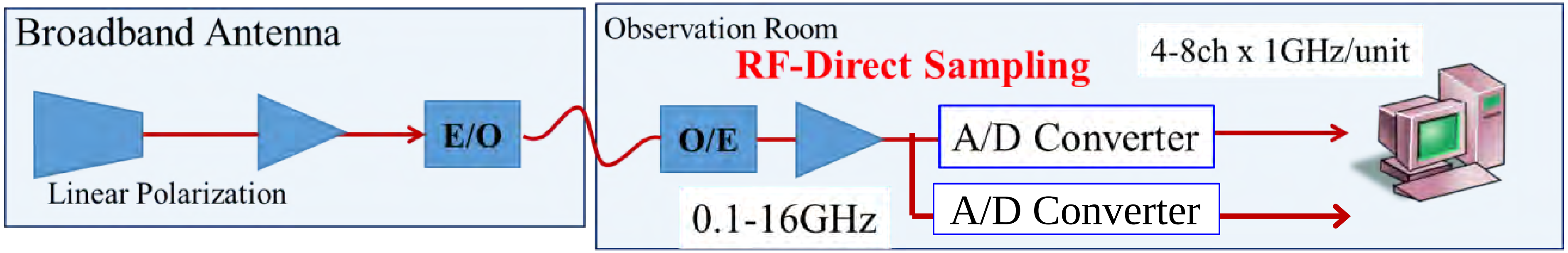
Broadband group delay

- Broadband VLBI, 3-14 GHz range
  One order large bandwidth
  → one order fine delay precision.

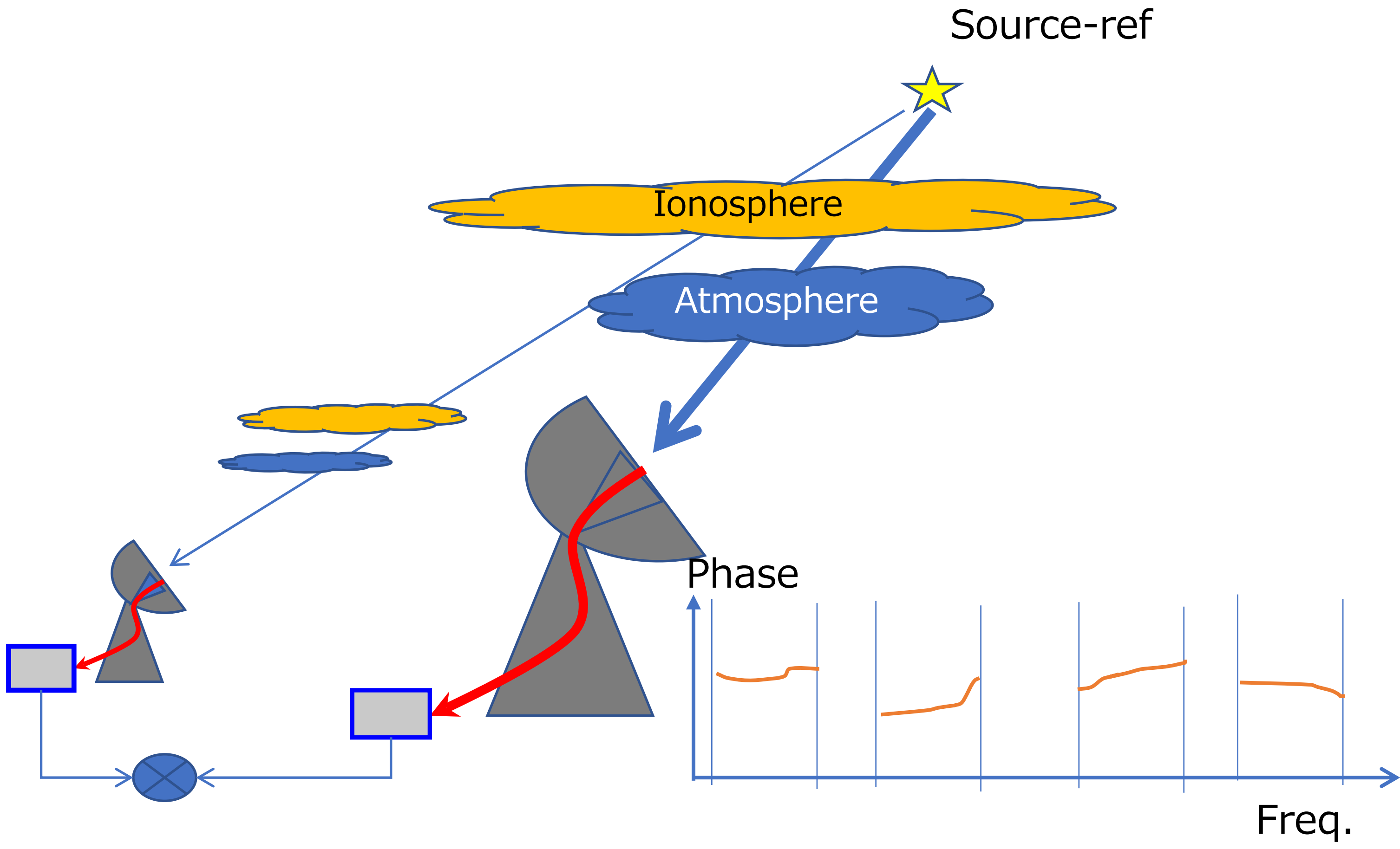


- **RF Direct Sampling**
  - Digitized without analog Frequency Conversion
  - Advantage at Phase stability



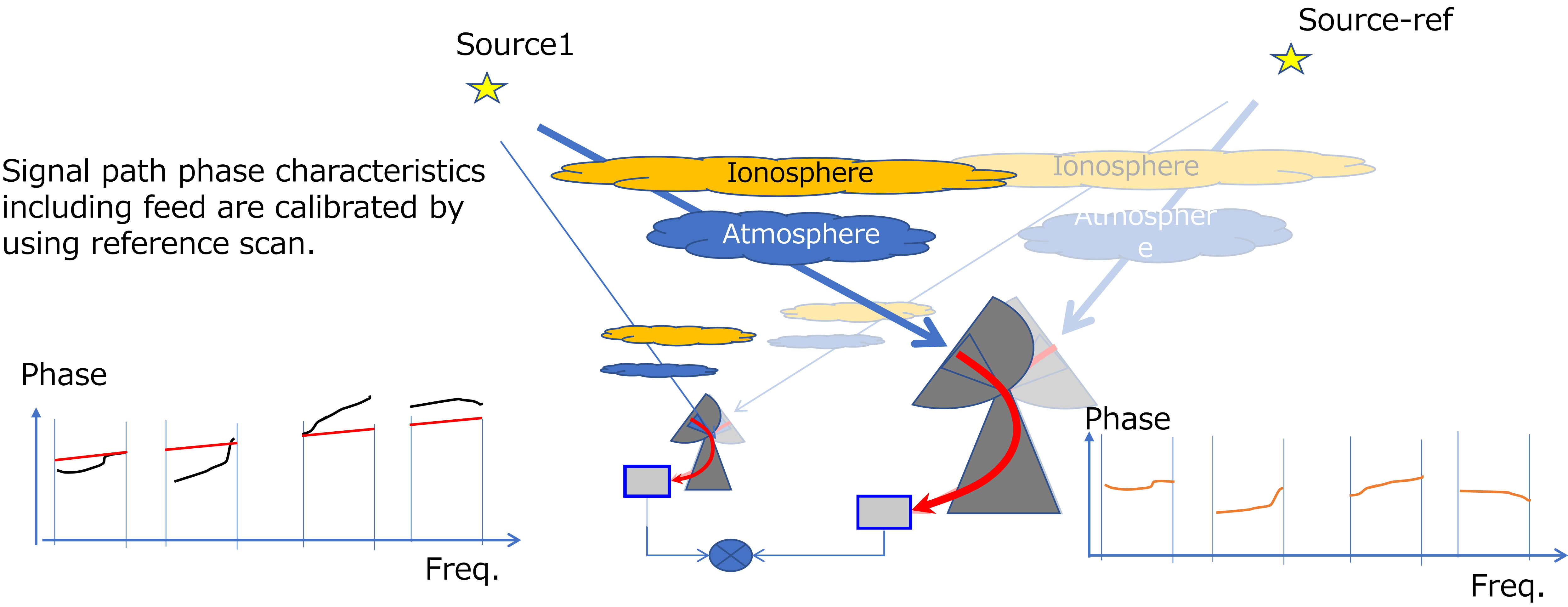


Procedure of Broadband Phase Calibration with radio source

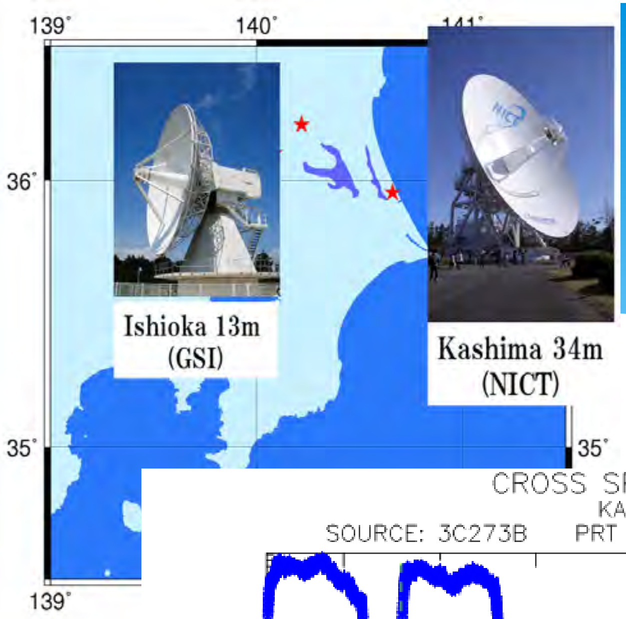


Procedure of Broadband Phase Calibration with radio source

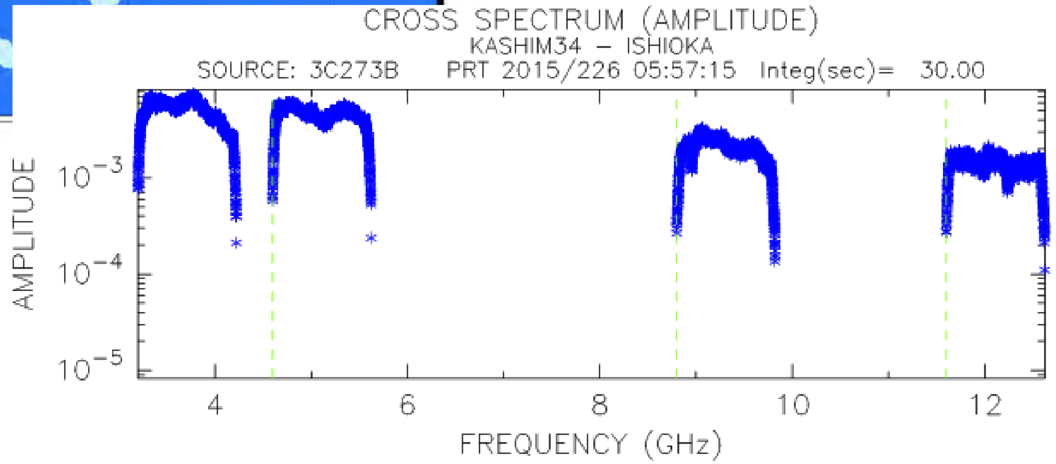
Signal path phase characteristics including feed are calibrated by using reference scan.

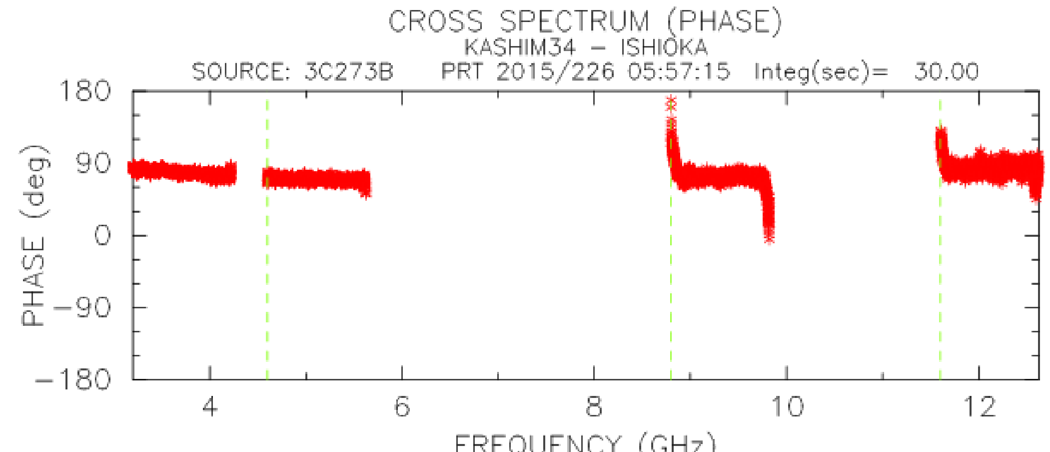


Bandwidth Synthesis

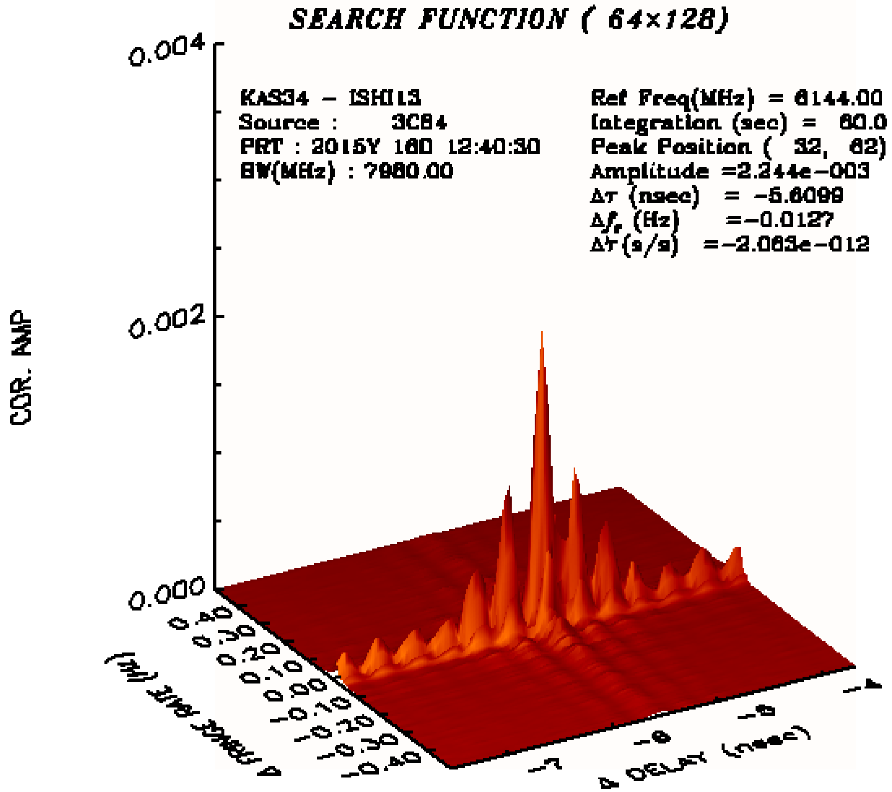


Cross spectrum

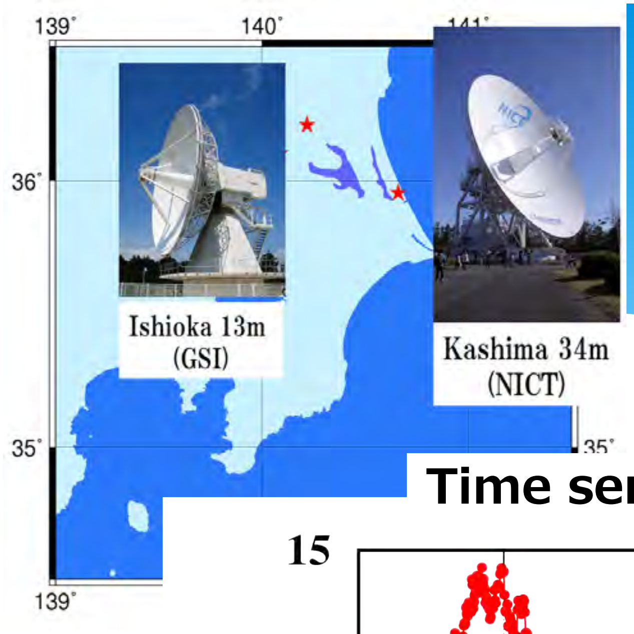




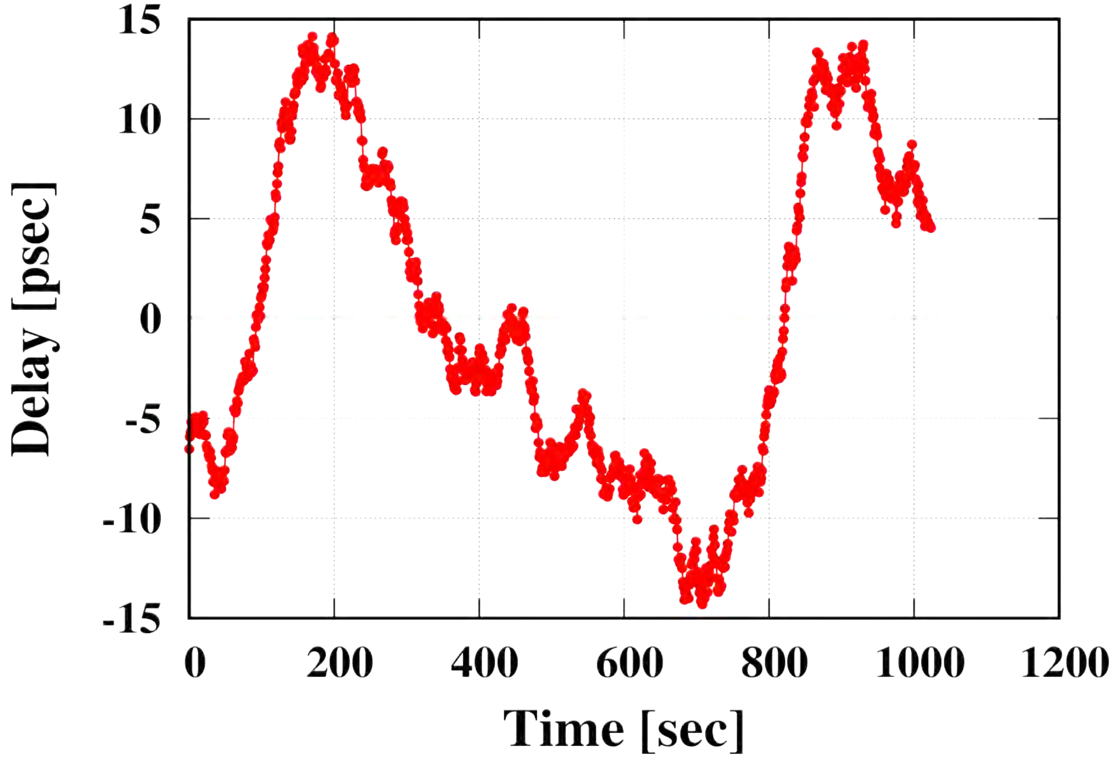
Delay resolution function



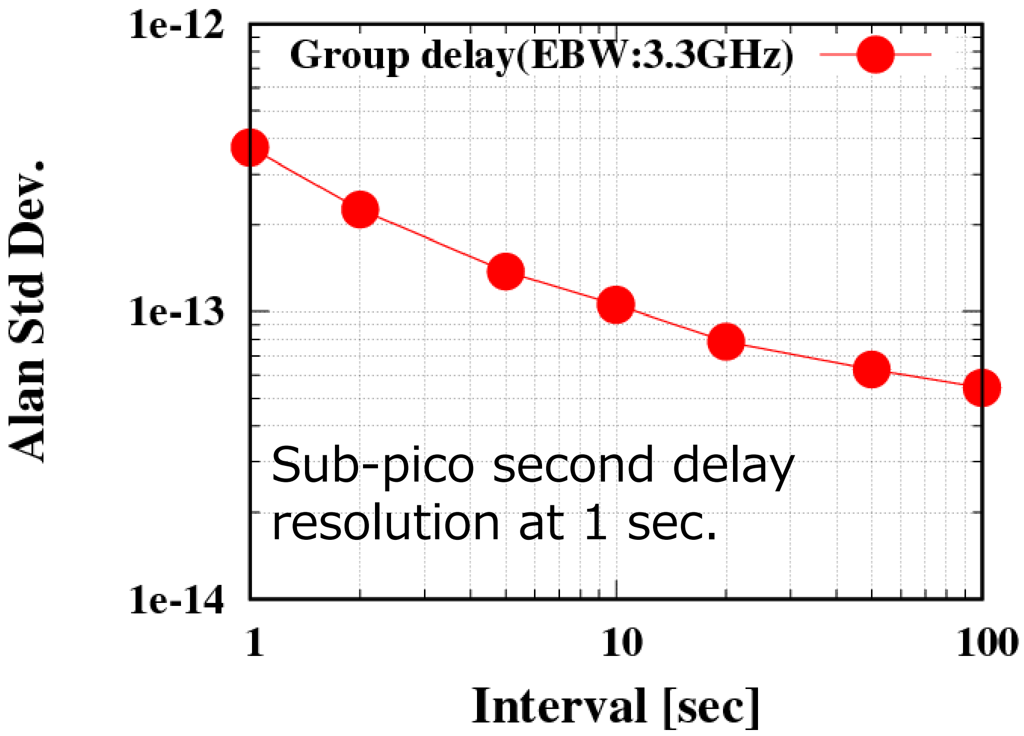
Broadband group delay (3.2-12.6GHz)



Time series of delay residual



Allan Standard Deviation



Node-Hub Style VLBI (using closure delay)

■**Boosting SNR:**

Poor SNR between small antenna pair is recovered by joint observation with high gain antenna.

$$\mathrm{SNR} \propto S\, D_1 D_2 \sqrt{\frac{\eta_1}{T_{sys1}} \cdot \frac{\eta_2}{T_{sys2}}}$$

D_n : Diameter
S : Radio Flux
η_n : Efficiency
T_{sys}: System noise.

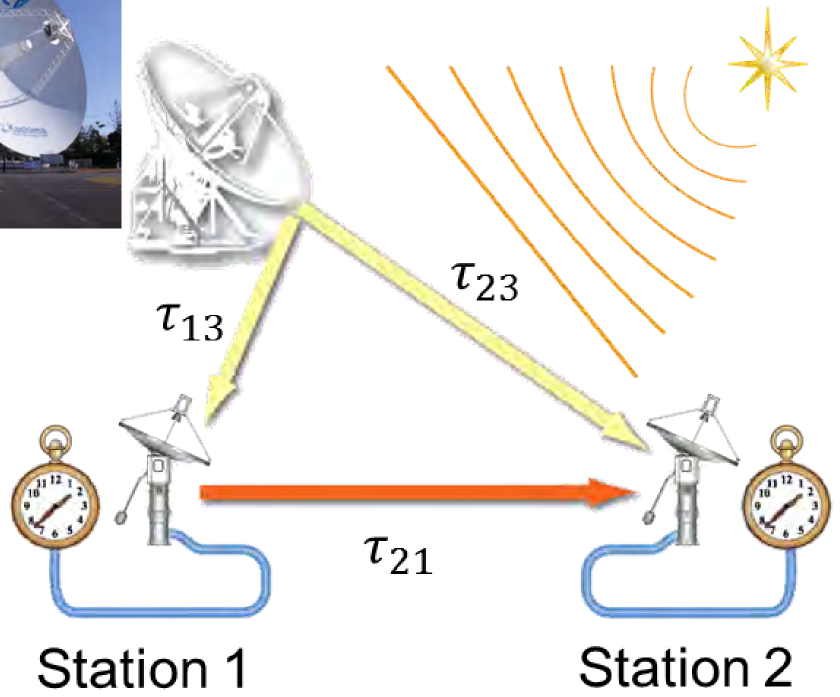
■**Cancel effect:** Large station(Gravitational Deformation, Cable delay)

■**Easy deployment**(Small antenna):

low-cost, transportable

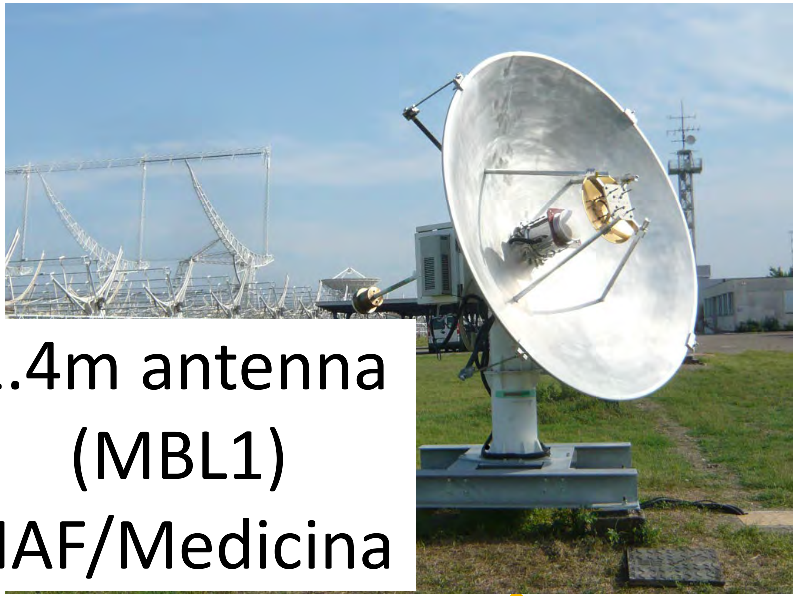
■**Potential advantage:**

■mitigation of radio source structure

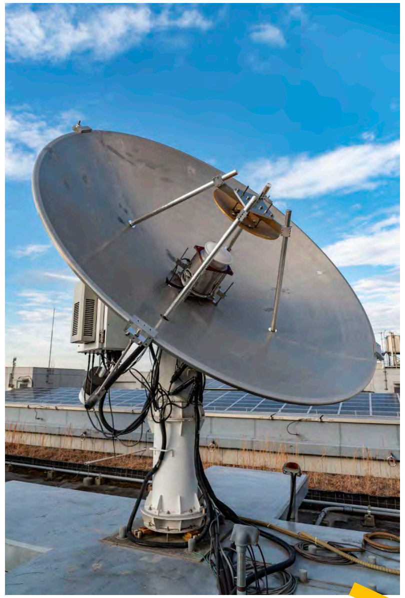


$$\boldsymbol{\tau_{21} = \tau_{13} - \tau_{23}}$$

Three Broadband VLBI Stations

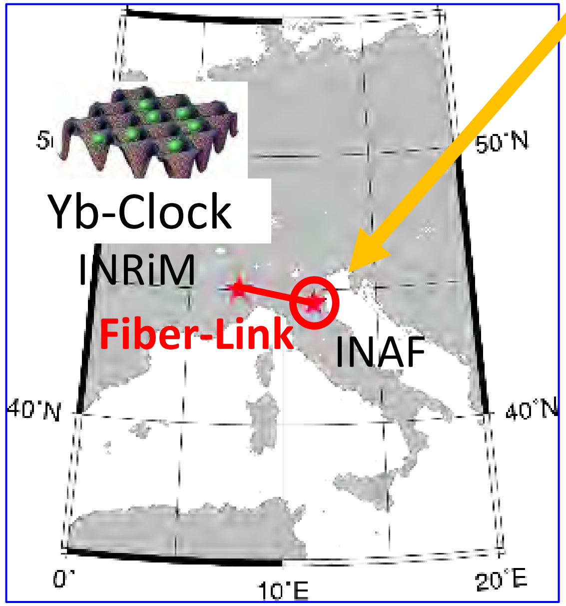


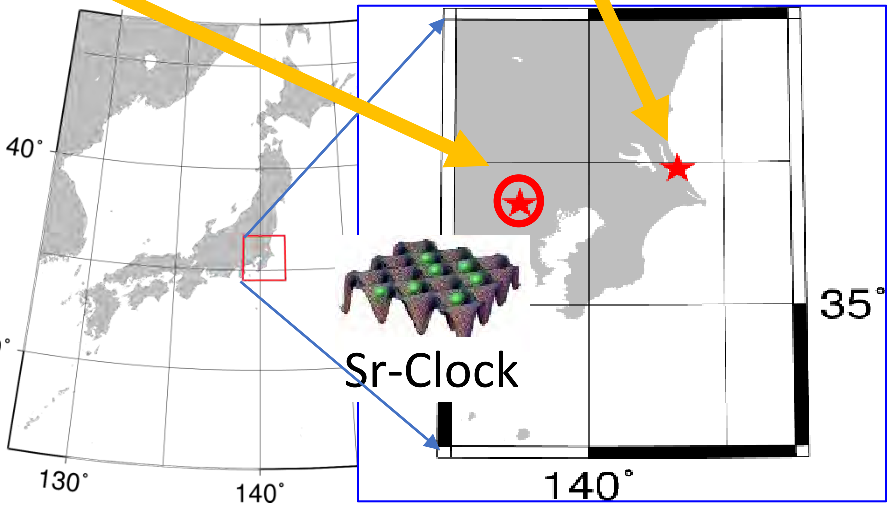
2.4m antenna
(MBL1)
INAF/Medicina



2.4m antenna
(MBL2)
NICT/Koganei

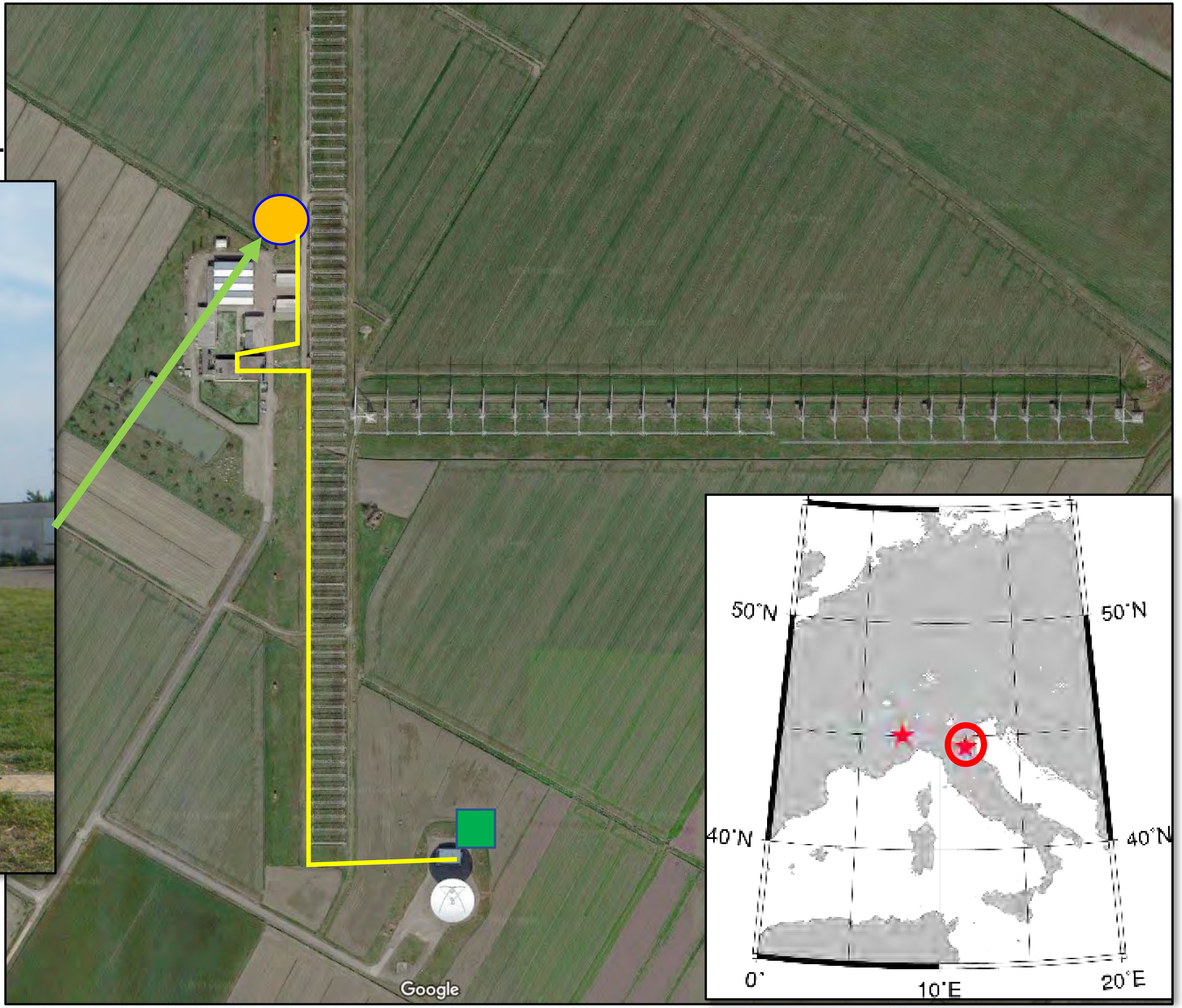
34m Diameter
(Kashima34)
NICT/Kashima





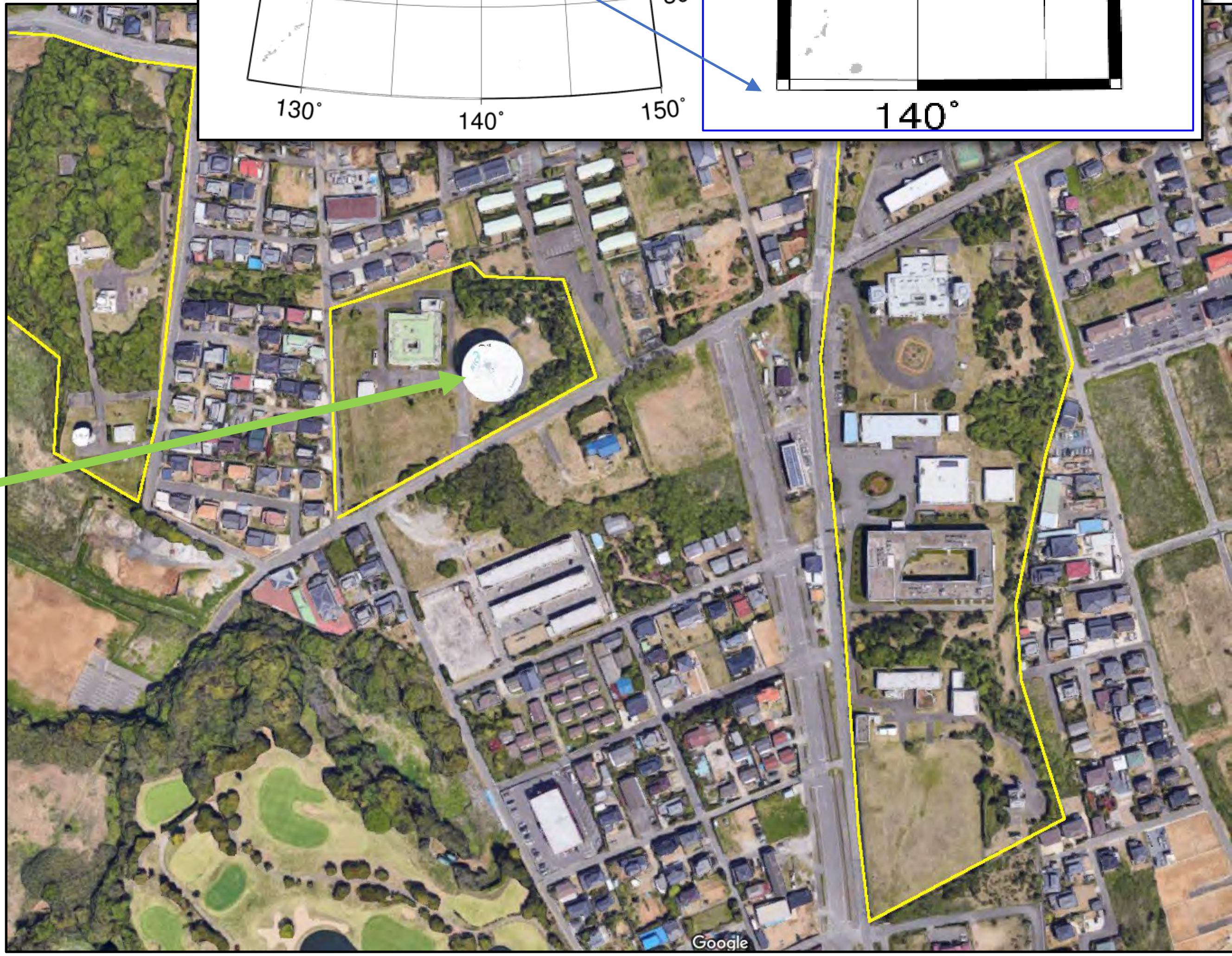
INAF/IRA Medicina Radio Astronomical Observatory

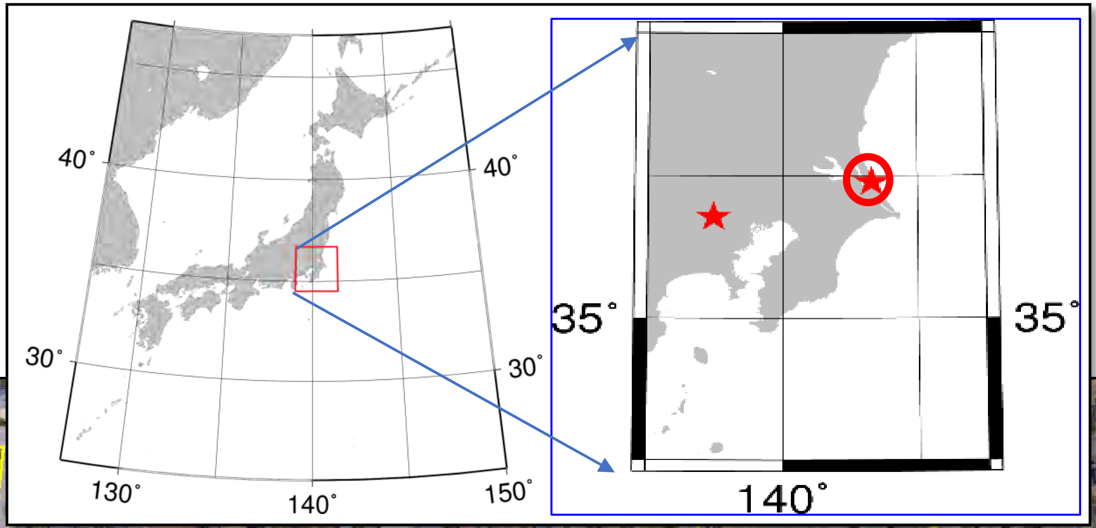
2.4 m diameter antenna MBL1



NICT / Kashima Space Technology Center

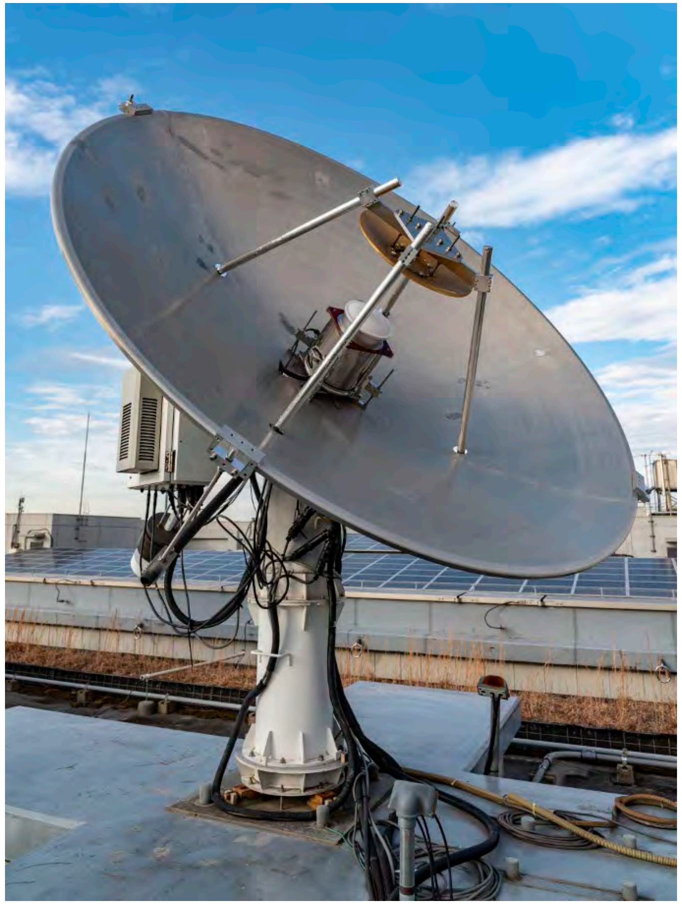
34 m diameter antenna Kashima34

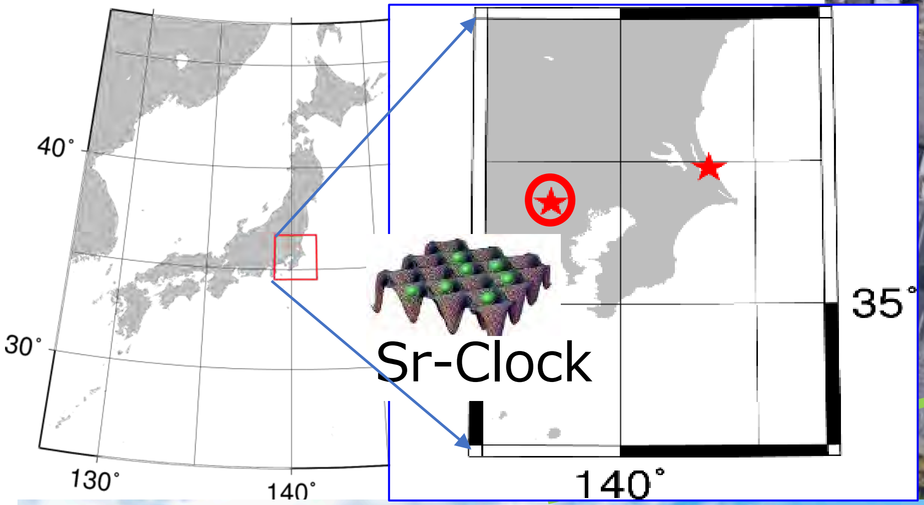




NICT/ Koganei Headquarters

2.4m Diameter Antenna(MBL2)



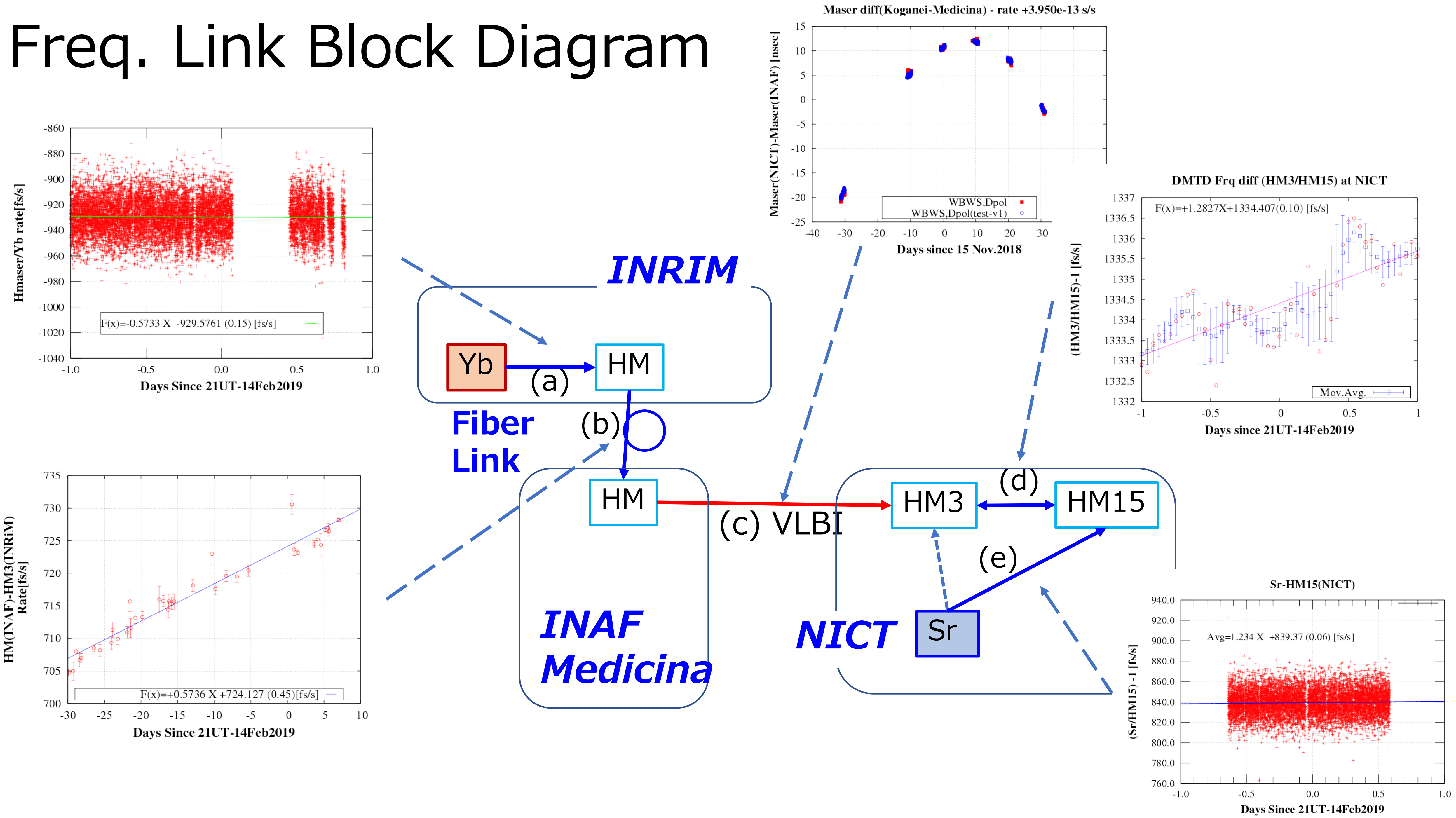


MBL2 and TWSTFT Antenna

VLBI Experiment list

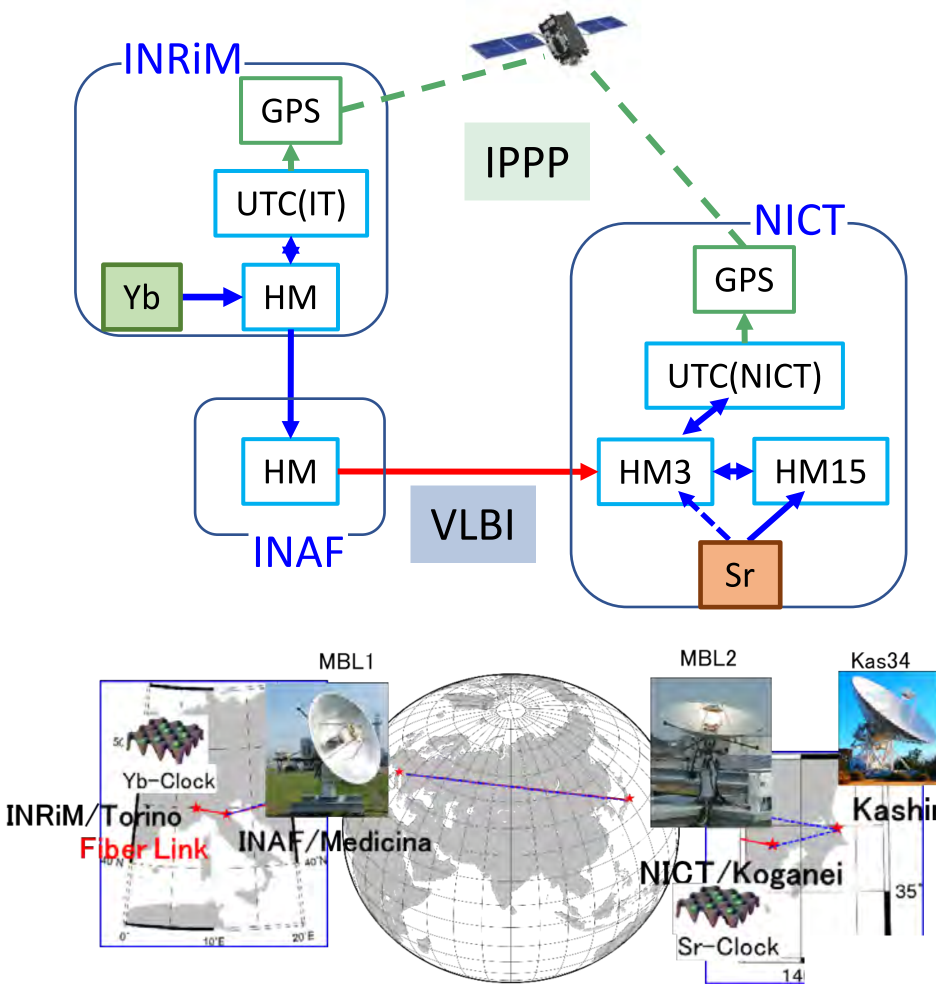
Exp Date	MJD	Duration [h]	# scans	Residual [ps]
14-15 Oct. 2018	58406	29	1155	32
04-05 Nov. 2018	58426	31	1409	39
14-15 Nov. 2018	58436	29	1417	23
24-25 Nov. 2018	58447	29	1281	28
04-05 Dec. 2018	58457	29	1344	33
15-16 Dec. 2018	58467	30	1379	26
25-26 Dec. 2018	58477	29	1442	22
15-16 Jan. 2019	58498	29	1363	24
25-26 Jan. 2019	58508	28	1336	26
24-25 Feb. 2019	58528	36	1342	29

Freq. Link Block Diagram

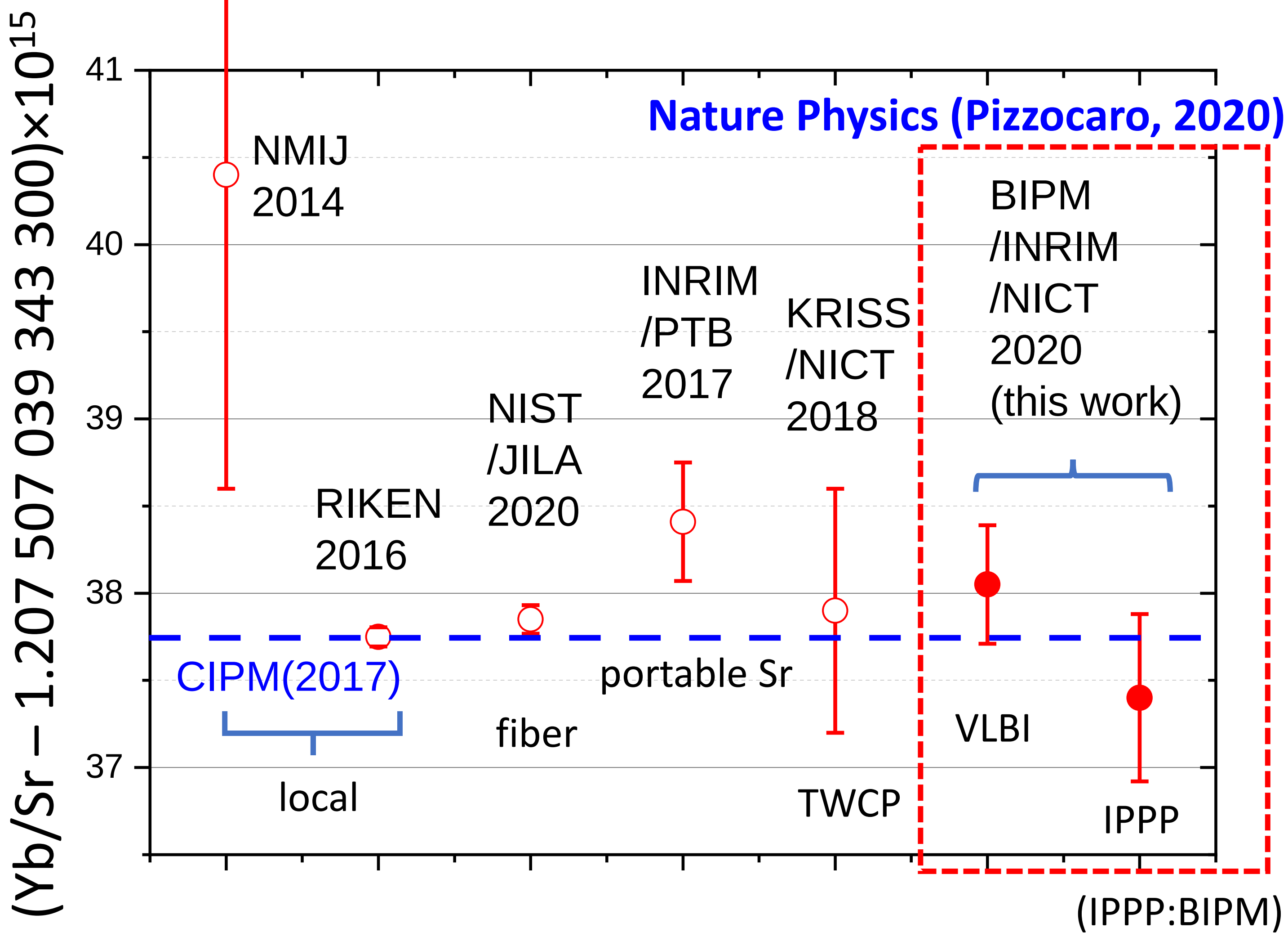


Yb/Sr Freq. Link: Comparison

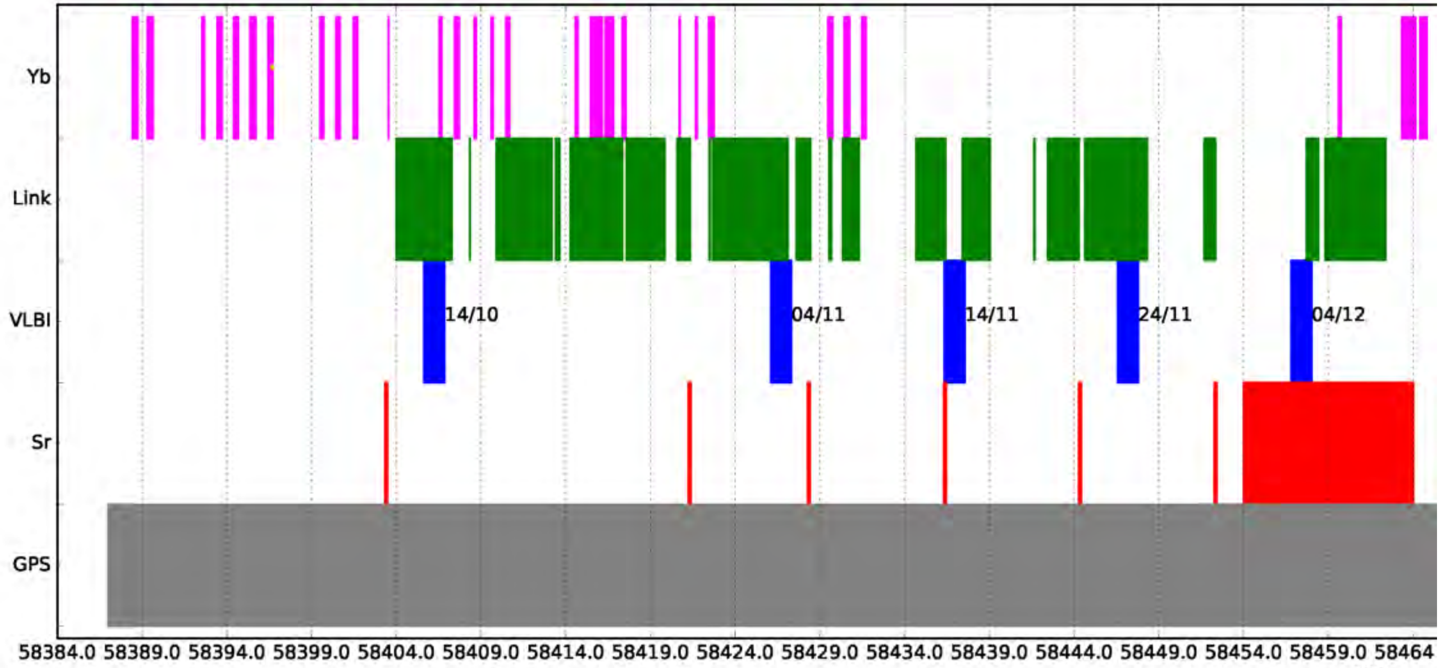
Best precision for 9000 km distance

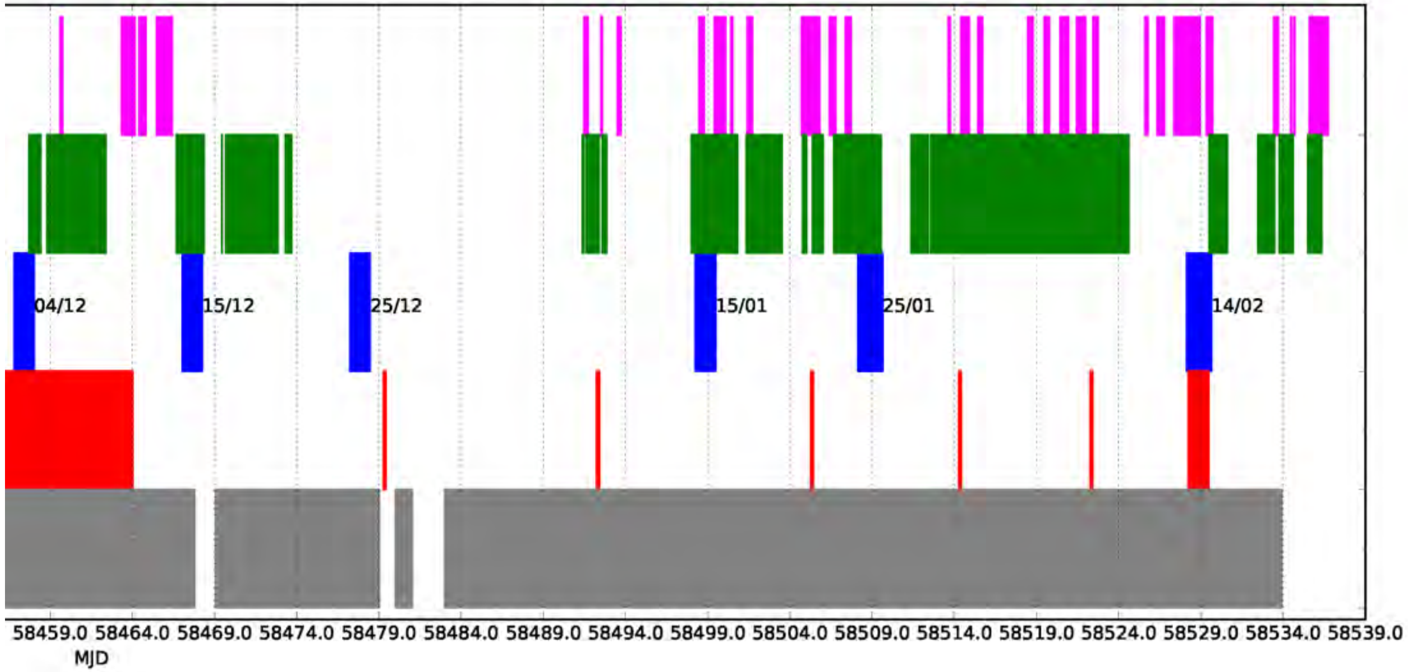


y(Yb/Sr)=2.5(2.8)x10^{-16} (VLBI)



Yb-Sr Link Experiment Time Alignment





Yb

Fiber Link

VLBI

Sr

GPS

Uncertainty budget of VLBI and GPS-link

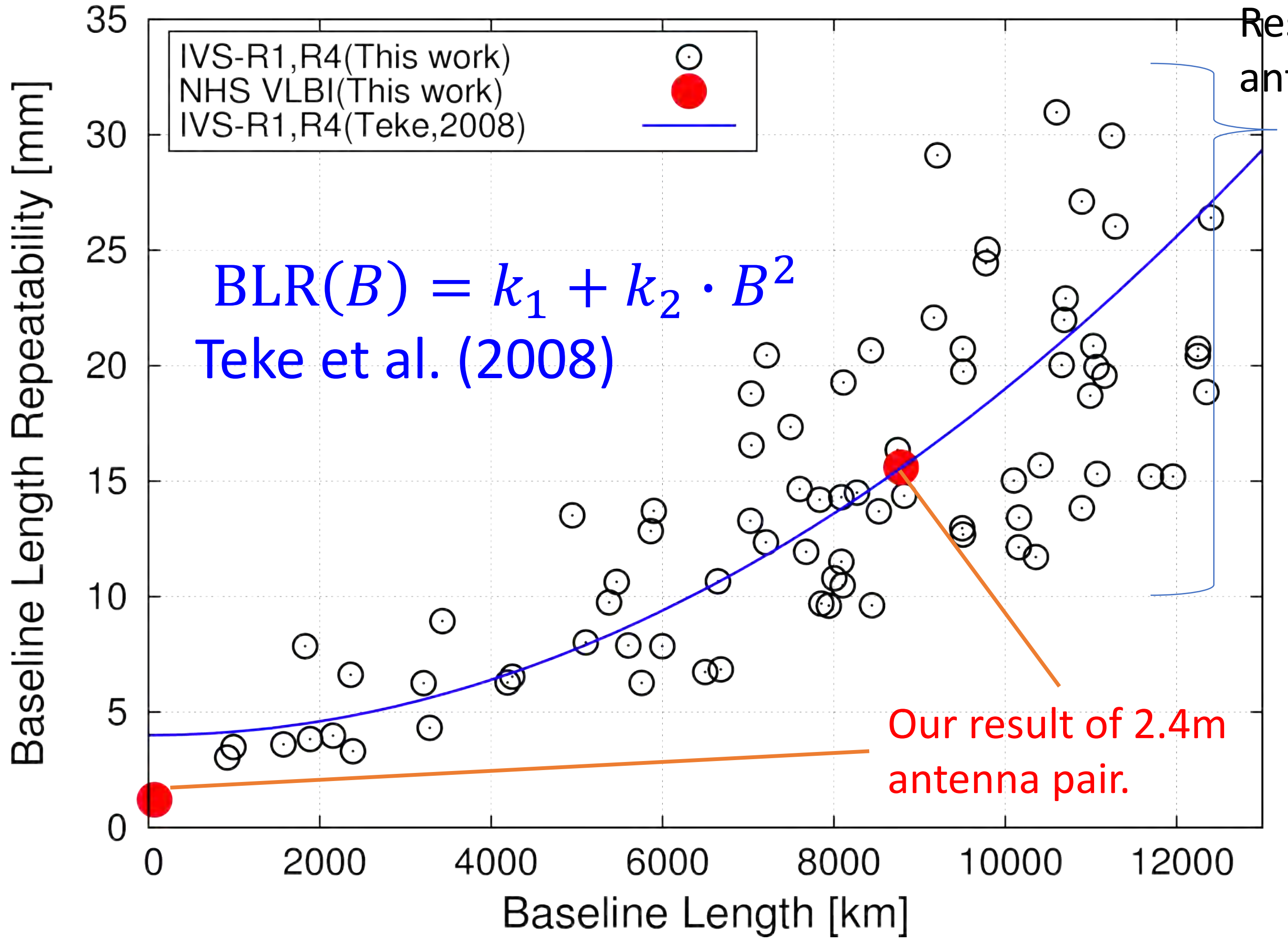
Table 2 | Uncertainty budgets for the ratio and closure measurements

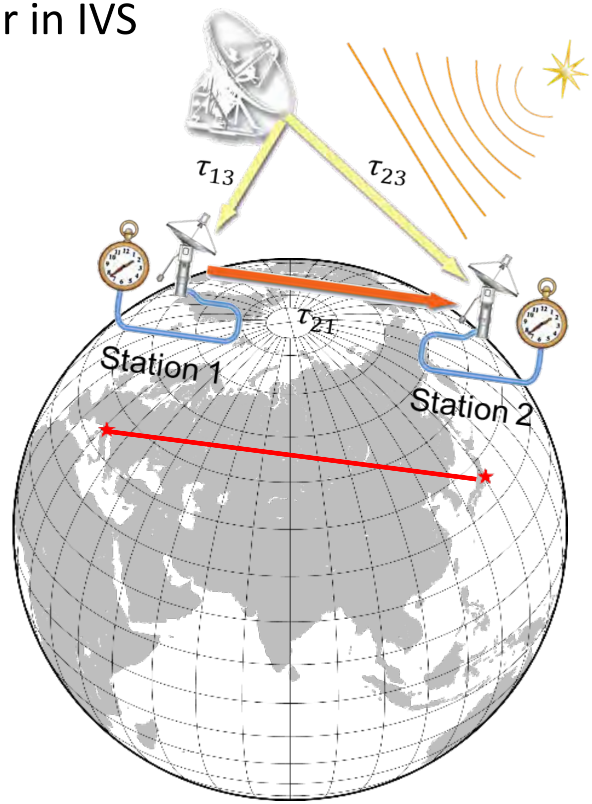
Yb/Sr ratio via VLBI		Yb/Sr ratio via IPPP		Closure	
Contribution	**Uncertainty ($\times 10^{-16}$)**	**Contribution**	**Uncertainty ($\times 10^{-16}$)**	**Contribution**	**Uncertainty ($\times 10^{-16}$)**
VLBI	0.9	IPPP	2.6	VLBI	0.7
Clocks	0.9	Clocks	0.9	IPPP	2.3
Combs (microwave/optical)	1.1	Combs (microwave/optical)	1.1	Combs (microwave/optical)	1.1
Extrapolation	2.2	Extrapolation	2.6	Extrapolation	1.9
Optical link	<0.1			Optical link	<0.1
Total	2.8	Total	4.0	Total	3.2

The listed uncertainties are calculated for the weighted average of the points in Fig. 2a and the weighted average of their difference. The VLBI and IPPP uncertainties are the statistical contribution for the frequency transfer. The clock contributions consist of the systematic uncertainties of both clocks, including the gravitational redshift. The extrapolation uncertainty is a statistical uncertainty due to the intermittent operations of the optical clocks and the optical link. The uncertainty for the combs arises from their accuracy and from the instability in the microwave-to-optical conversions. The optical link contribution is negligible for the present measurement. All uncertainties correspond to 1 s.d.

Baseline Length Repeatability (BLR)

NHS VLBI observation with 2.4m-2.4m baseline demonstrated comparable BLR performance with IVS-R1,R4 sessions.





Sekido et al.,(2021) J. Geodesy

Uncertainty Budget of our Broadband VLBI observation (SNR, Instrument)

$$\sigma_{\tau,\mathrm{obs}}^2 = \sigma_{\tau,\mathrm{SNR}}^2 + \sigma_{\tau,\mathrm{inst}}^2 + \sigma_{\tau,\mathrm{atm}}^2 + \sigma_{\tau,\mathrm{ion}}^2 + \sigma_{\tau,\mathrm{str}}^2$$

1. Sensitivity

Effective Band Width=2.8 GHz, Delay precision $\sigma_\tau = 1/(2\pi \cdot \mathrm{SNR} \cdot \mathrm{EBW})$

-> 6 ps with SNR=10

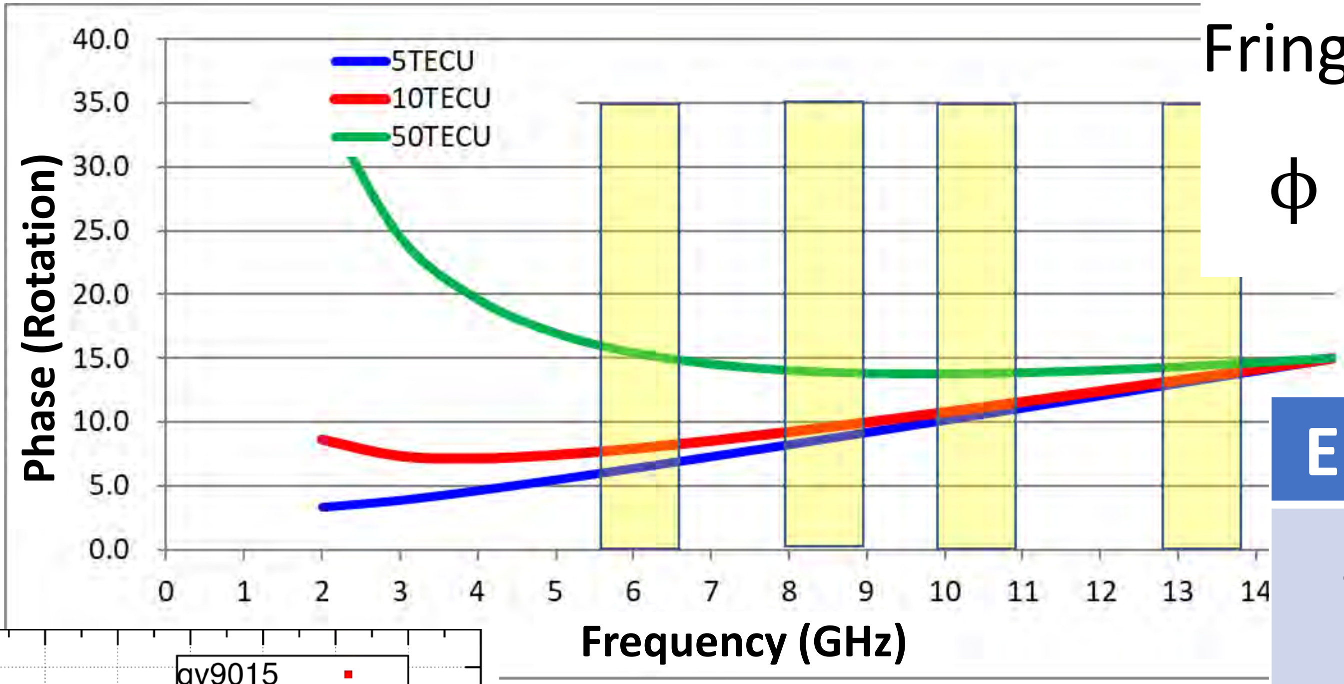
2. Instrumental

- Opt-Fiber 600 m (Medicina) (cff.5.2x10^{-7} /K) 5 K Temp. Variation in the trench→7.6 ps
- Opt-Fiber 50 m (Koganei) 15 K Variation →1.9 ps
- Sampler :
  Temperature dependence 10 ps
  jitter : 0.2 ps
- Mechanical Stress (AZEL motion): 0.5 ps
- Total

$$\sqrt{7.6^2 + 1.9^2 + 10^2 + 0.2^2 + 0.5^2} = 12.7 \text{ ps}$$

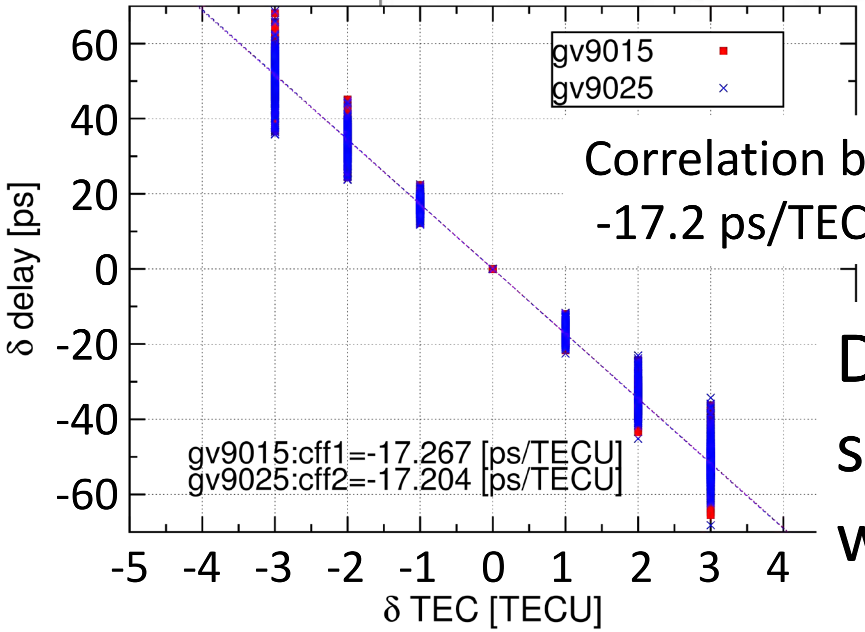
Error Source	uncertainty
Sensitivity (∝1/SNR)	6.4 ps
Instrumental	12.7 ps
Atmosphere	7.9 ps
Ionosphere	1.7～17 ps
Radio Source Structure	22-33 ps

Uncertainty Budget of Broadband VLBI (Ionosphere)



Fringe Phase

$$\phi = \tau_g \cdot f - A\frac{\Delta \mathrm{TEC}}{f} + \phi_0$$



Correlation between TEC and Group Delay
-17.2 ps/TECU

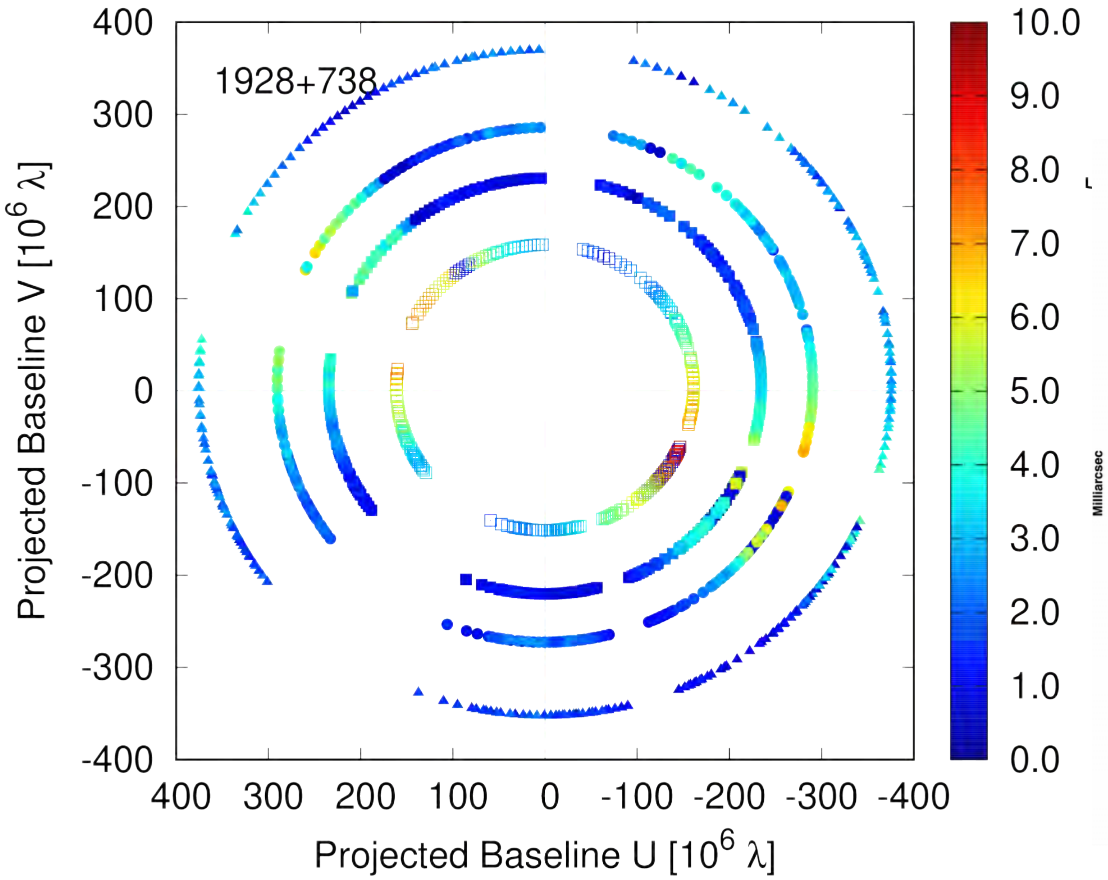
Due to limited SNR of small antenna, TEC error was 0.1-1 TECU.

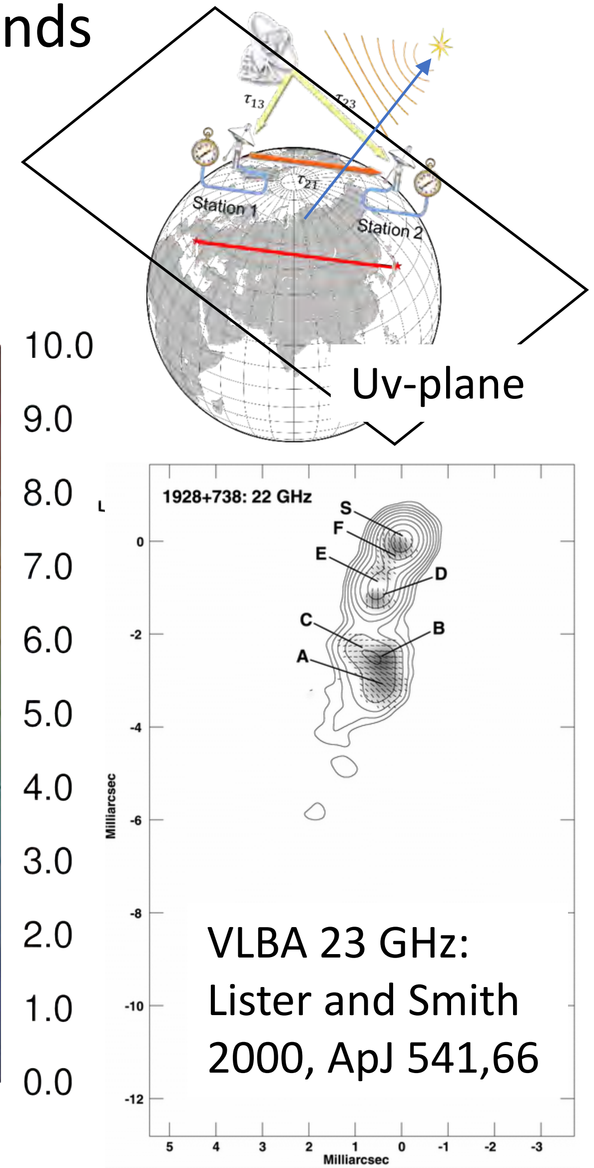
Error Source	uncertainty
Sensitivity (∝1/SNR)	6.4 ps
Instrumental	12.7 ps
Atmosphere	7.9 ps
Ionosphere	1.7～17 ps
Radio Source Structure	22-33 ps

Radio Source Structure appeared in Correlation Amplitude on 2.4m-34m (8800km) baseline

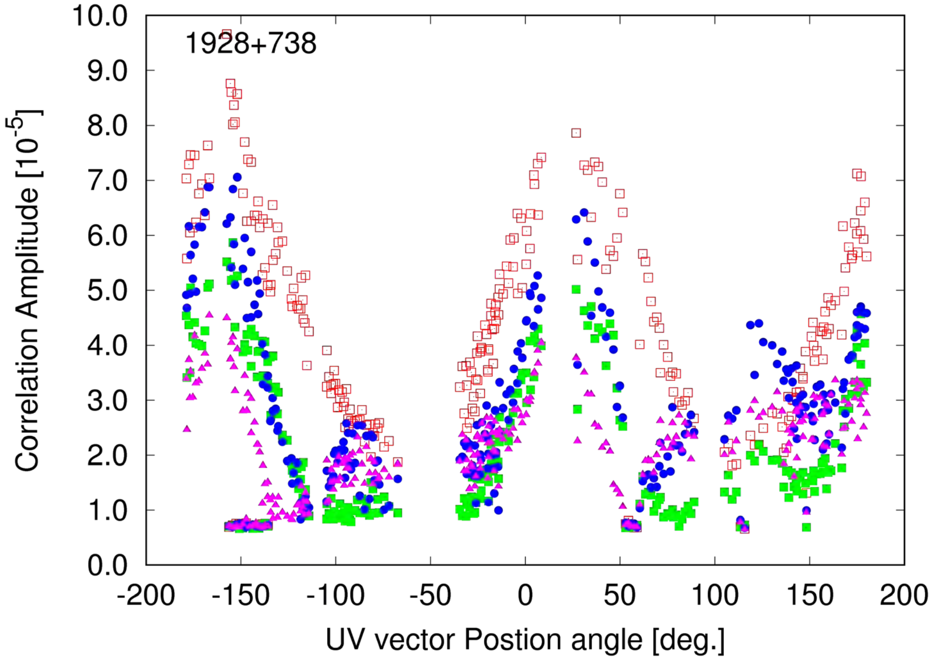
for four (6.0, 8.5, 10.4, 13.3 GHz) bands

An example of a source with large amplitude variation.





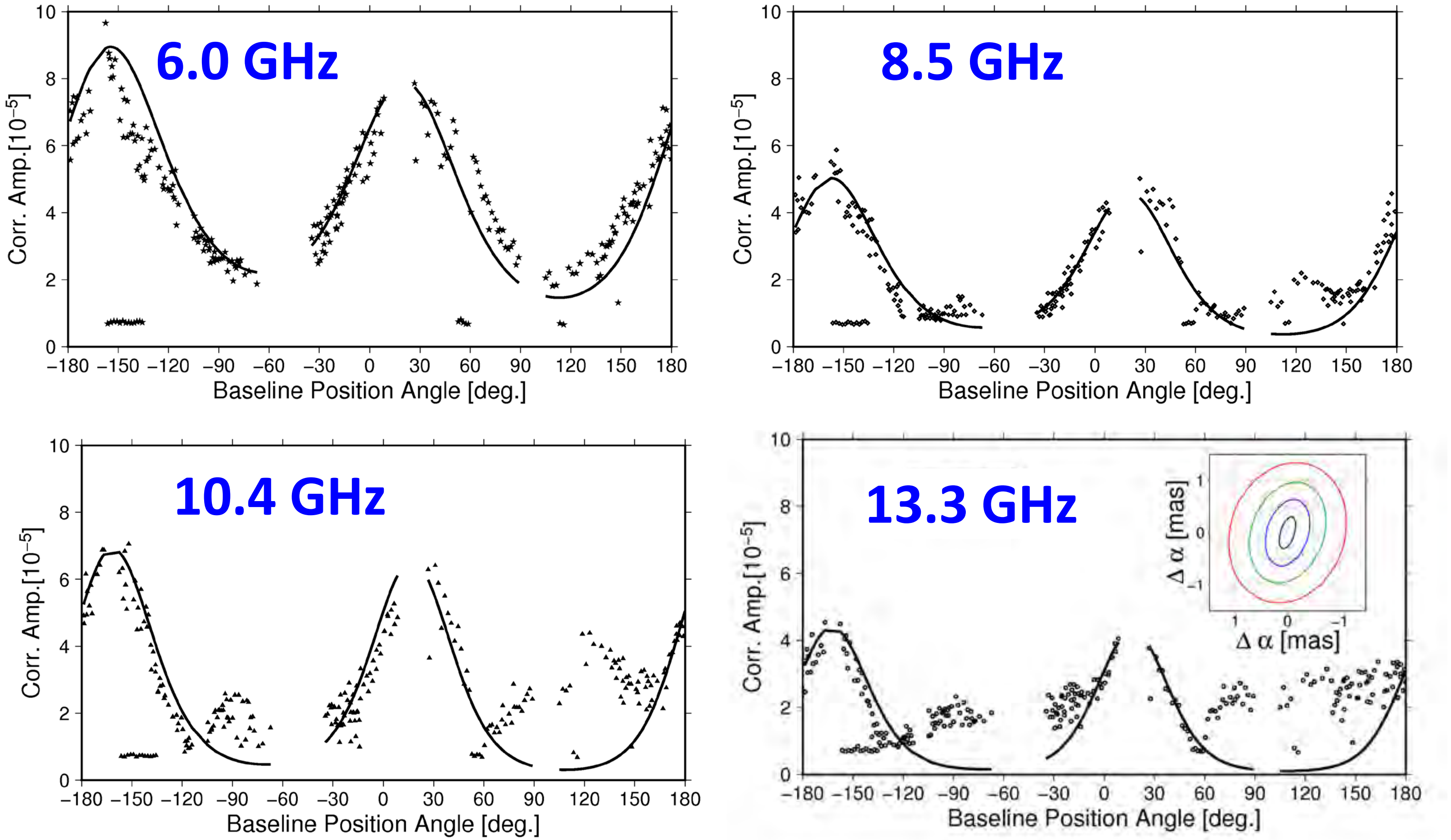
Group Delay is affected by both asymmetricity and frequency dependence of source structure.



Uncertainty Budget of our Broadband VLBI (Source Structure)

Frequency dependent source structure and barycenter shift cause **group delay error.** In addition, it also couple with **ionospheric TEC**.

Radio Source:1928+738



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Sensitivity (∝1/SNR)	6.4 ps
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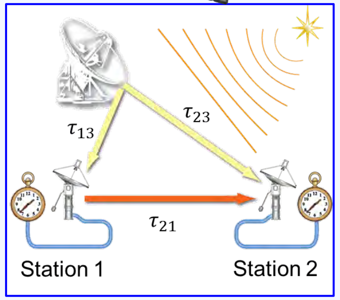
Summary

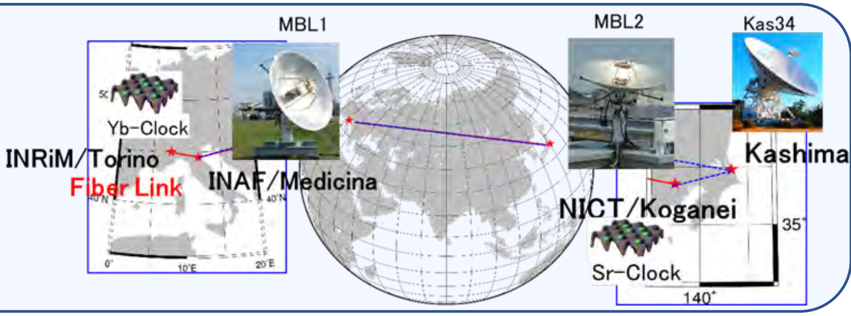
Development: Broadband VLBI system(Feed, RF Direct-Sampling) and transportable VLBI with Node-Hub Style scheme.





Freq. ratio Yb/Sr optical clock was measured as $+2.5(2.8)\times10^{-16}$ on 9000 km distance.

Nature physics (Pizzocaro et al.,2020)



Error Budget of VLBI observation: Major delay error sources are

- **Ionospheric delay.** (2~17 ps)
- **Radio source structure** (~20-30 ps)
- Node-Hub Style VLBI has potential to reduce structure effect in group delay observable

Refer to J. Geodesy (Sekido et al.,2021) for technical detail

Thank you for your Attention

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