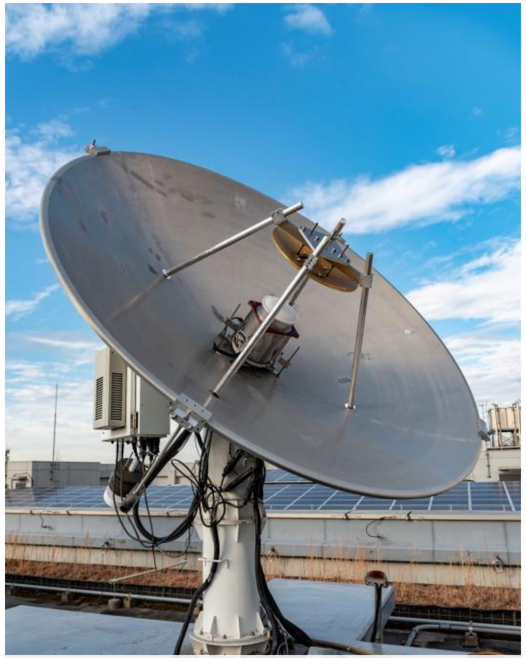
A Broadband VLBI experiment with transportable station between Japan and Italy

-RF Direct sampling and a new observation scheme using closure delay relation-


M.Sekido, K.Takefuji, H.Ujihara, T.Kondo, M.Tsutsumi, E.Kawai, H.Hidekazu, N.Nemitz, M.Pizzocaro, C.Clivati, F.Perini, M.Negusini, G.Maccaferri, R.Ricci, M.Roma, C.Bortolotti, G.Zacchiiroli, J.Roda, K.Namba, J.Komuro, Y.Okamoto, R.Takahashi, R.Ichikawa, T.Suzuyama, K.Watabe, J.Leute, G.Petit, Davide Calonico, Tetsuya Ido

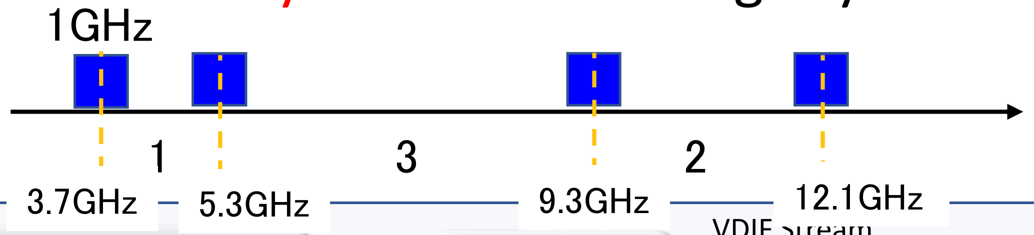
NICT
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
BIPM

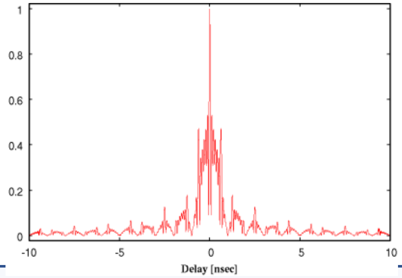
AGU fall meeting 16Dec. 2020

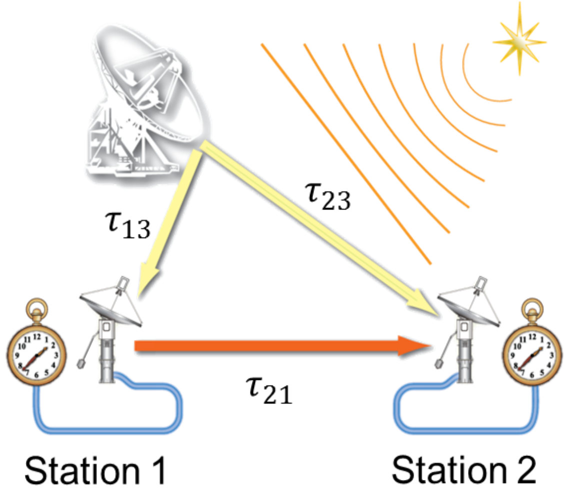
Project Overview

Purpose: High precision frequency comparison over intercontinental baseline toward re-definition of SI-second.

- ■Broad Radio Frequency：3.2-14 GHz (Almost VGOS compatible)
- ■Transportable Station: Node-Hub Style VLBI
- ■High data-rate acquisition： 4 band (1024MHz width/band)
  - ■Effective Bandwidth：3.3GHz (10 times wider than conventional）
  - ■Absolute delay :Free from ambiguity



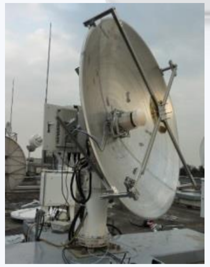


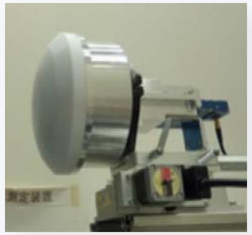


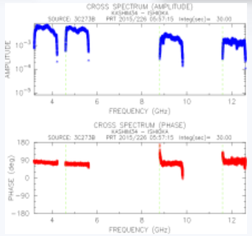
$$\tau_{21} = \tau_{13} - \tau_{23}$$

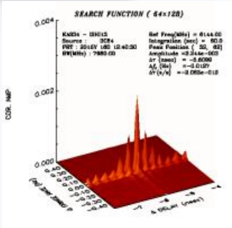
Broadband Feed for Cassegrain → RF-Direct Sampler → (VDIF Stream) → Recording → Correlation GICO3 → Broadband Synthesis → Mk3DB → Calc/Solve

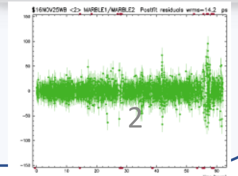
Compatible with Mk6, Flexbuf (jive5ab)







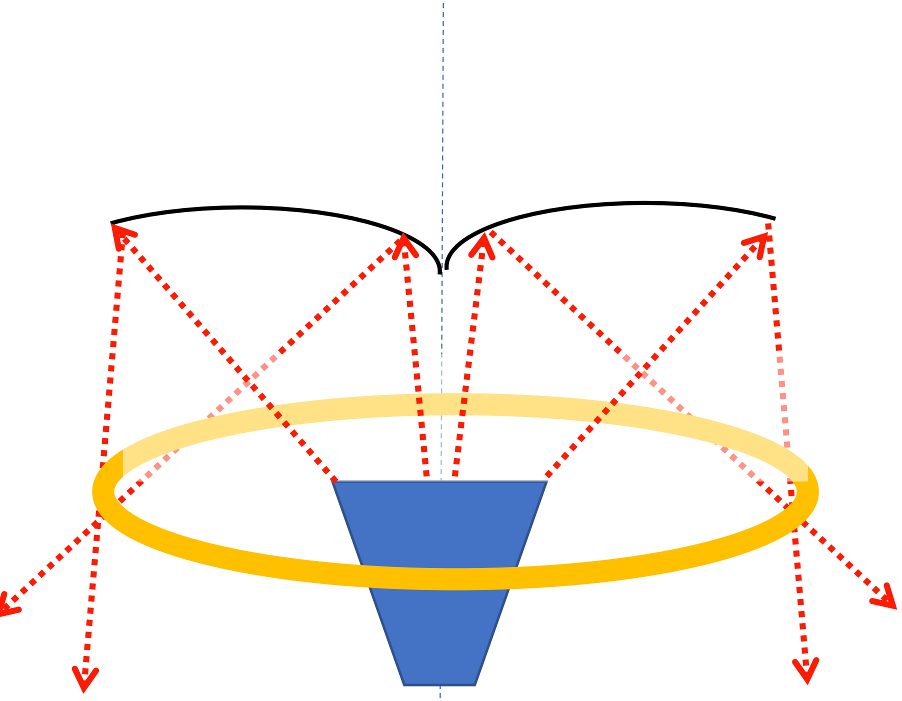




Broadband VLBI Development

Reason why NICT Developed own Broadband Feeds

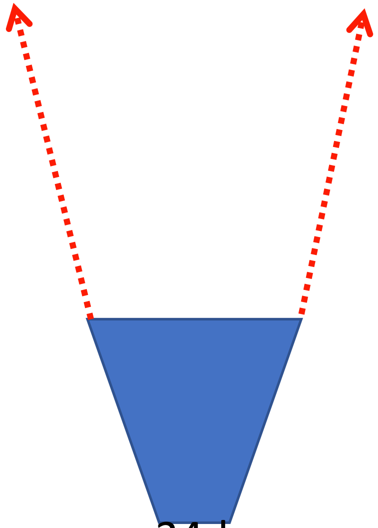
Requirement of **Broadband Frequency** and **Narrow beam width**



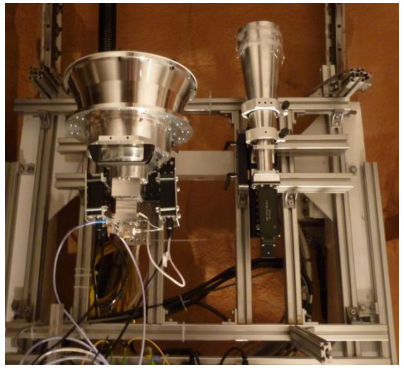
～120deg.

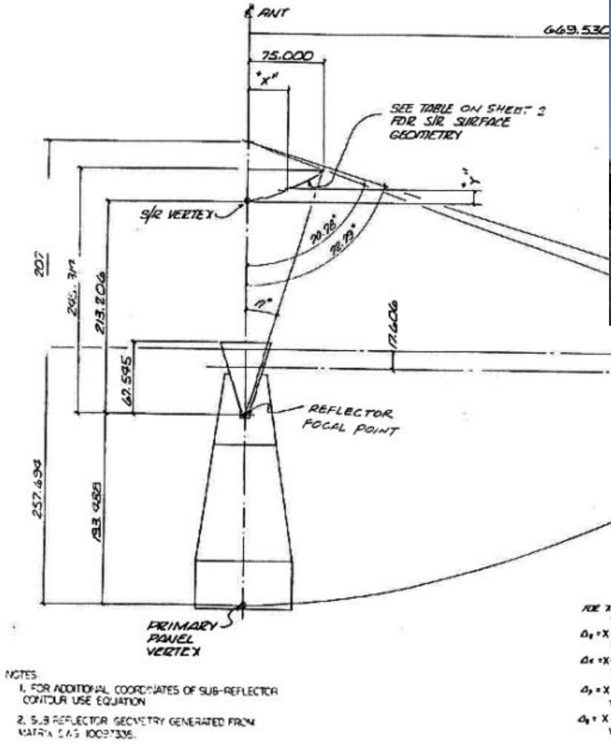
Eleven Feed

QRFH



～34deg.



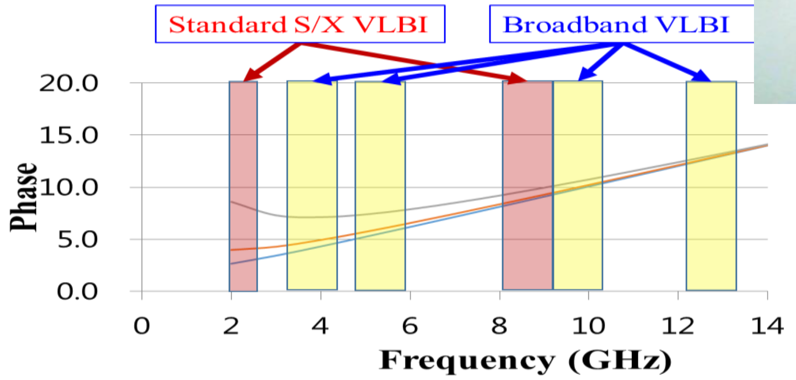


Broadband Feed and RF-Direct Sampling

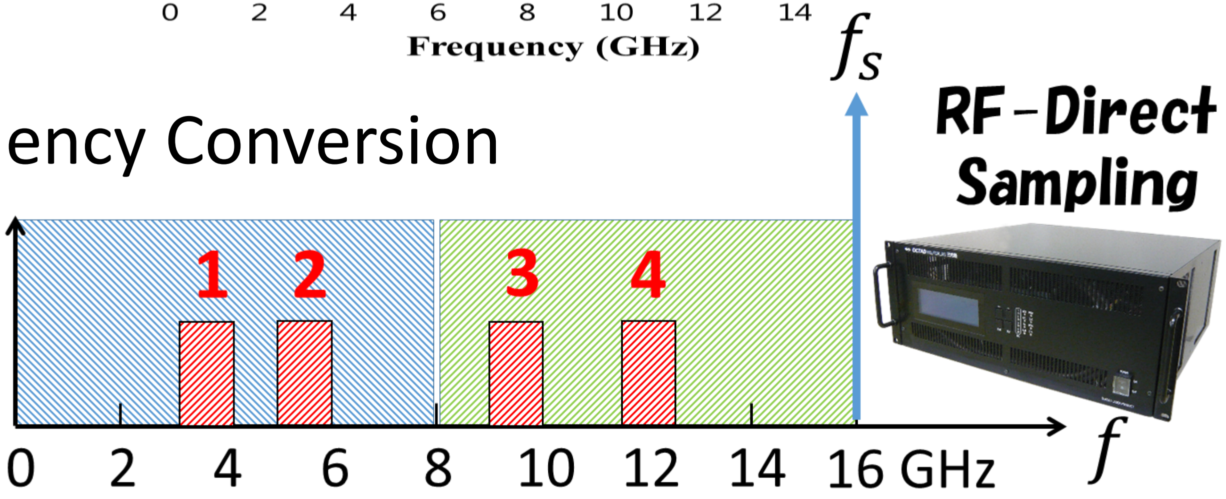
- Broadband VLBI, 3-14GHz range

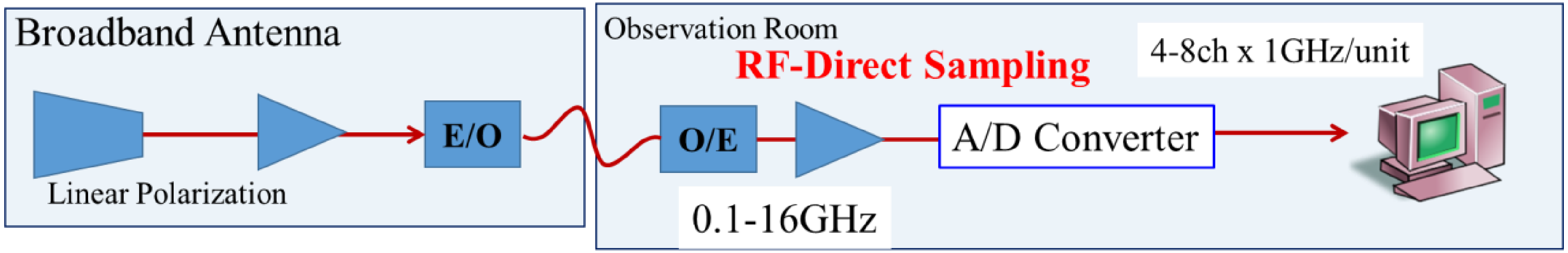
  One order large bandwidth

  → one order fine delay precision.



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





A Novel features of this system

Node-Hub Style (using closure delay)

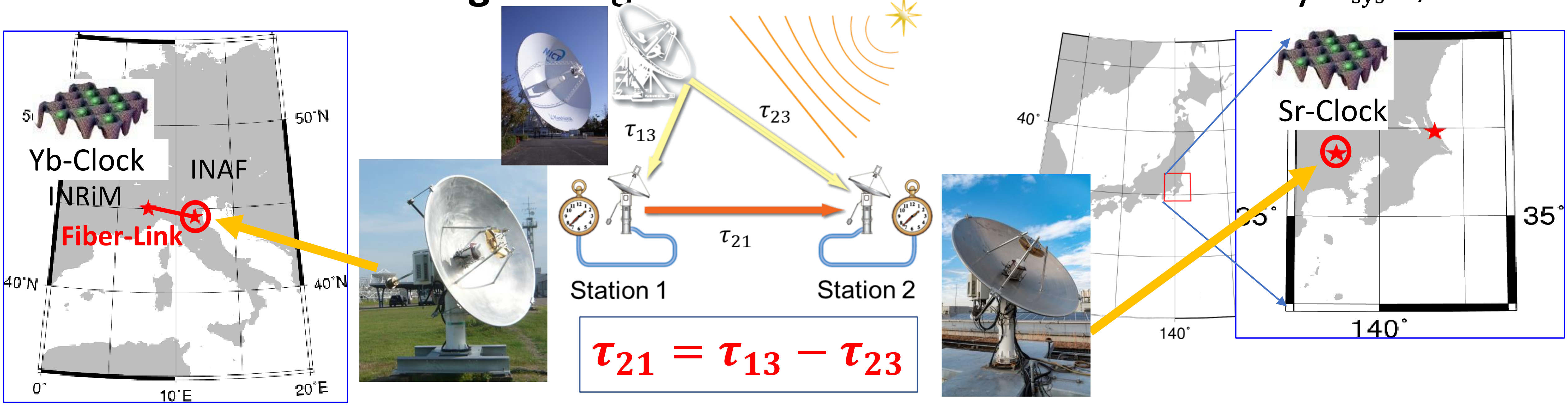
$$\tau_{21}^{NHS}(t_1) = \tau_{23}(t_1) - \tau_{13}(t_1) + \tau_{13}(t_1)\dot{\tau}_{21}(t_1)$$

$$\tau_{21}^{\mathrm{NHS}} - \tau_{21}^{\mathrm{true}} = (\tau_{31}^{\mathrm{str}} + \tau_{23}^{\mathrm{str}}) - \tau_{21}^{\mathrm{str}}.$$

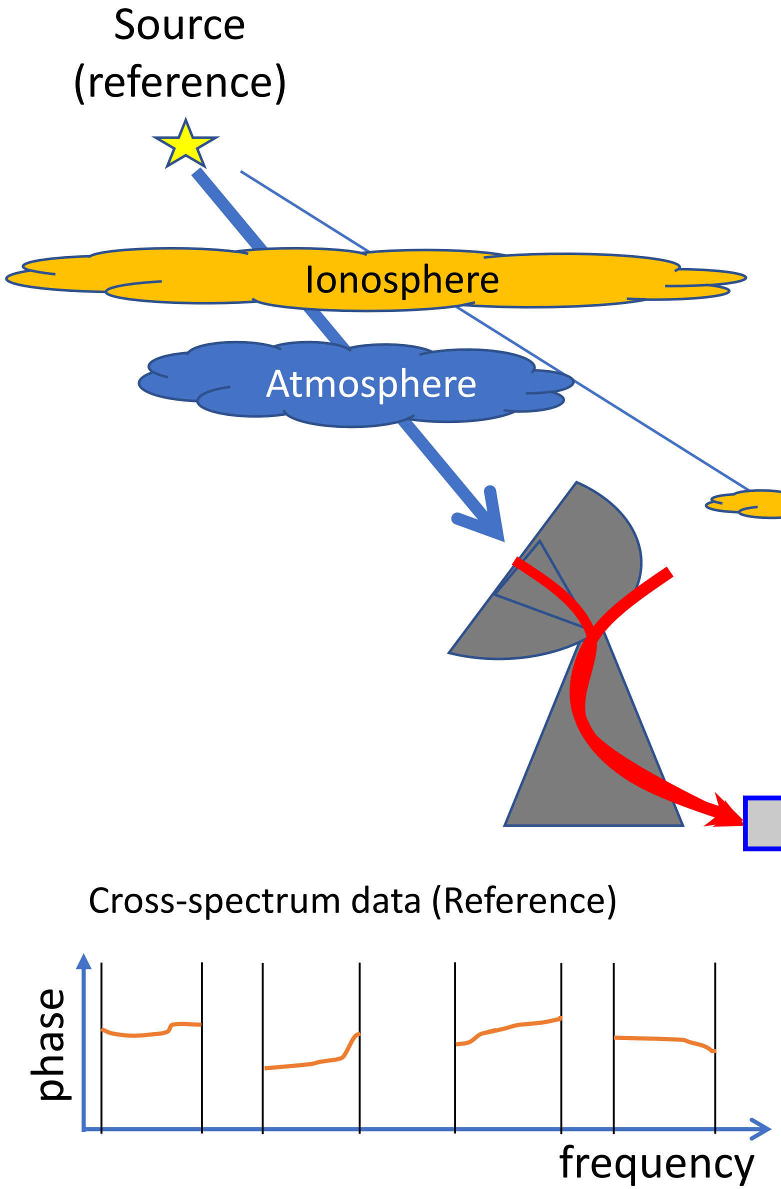
$$\mathrm{SNR} \propto S\, D_1 D_2 \sqrt{\frac{\eta_1}{T_{sys1}} \cdot \frac{\eta_2}{T_{sys2}}}$$

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

- **Cancel effect:** Large station(Grav. Deformation, Cable delay)
- **Easy deployment**(Small antenna): low-cost, transportable
- **Potential advantage:** mitigation of radio source structure delay



Broadband Phase Calibration with radio source



Observing a well-behaved source

Cross-spectrum containing differential phase characteristics of the signal chains is stored for calibration.

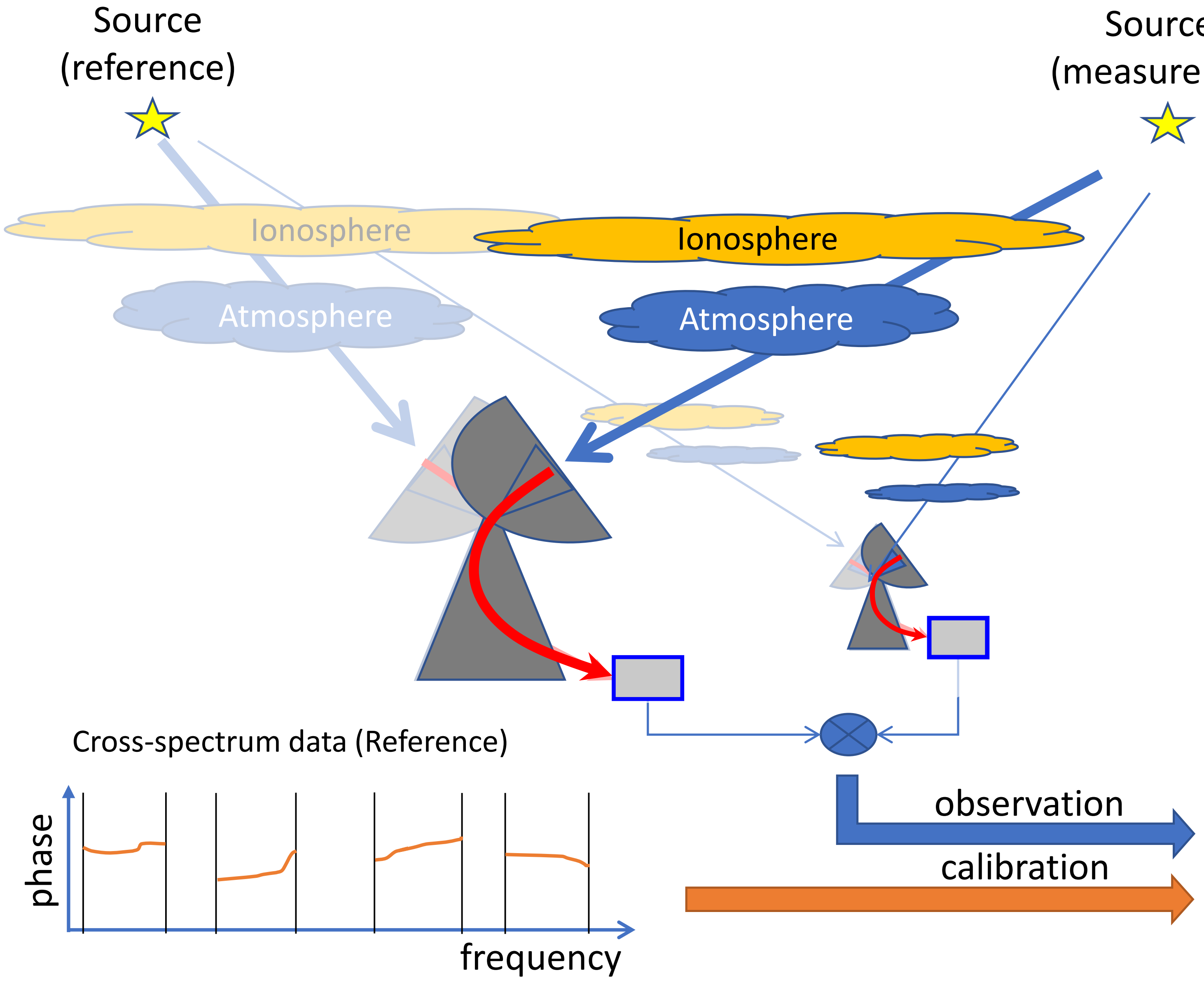
Broadband Phase Calibration with radio source

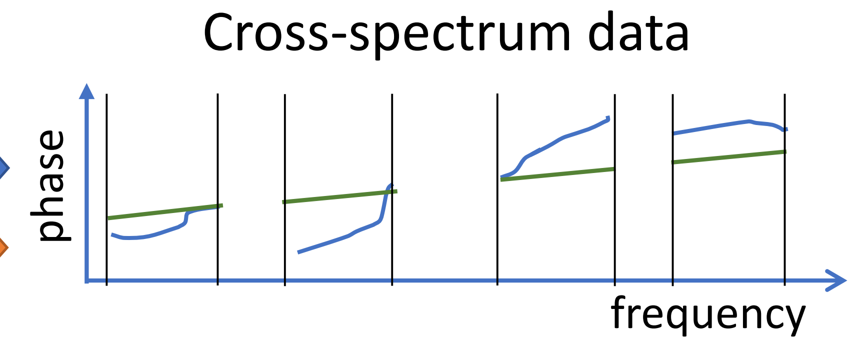
Observing a well-behaved source

Cross-spectrum containing differential phase characteristics of the signal chains is stored for calibration.

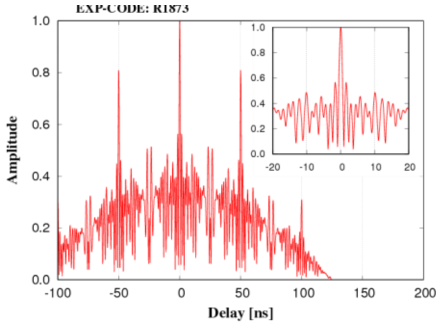
Radio-Source Phase-calibration (RSPcal)

Raw observations are calibrated based on **reference** data to obtain **corrected** data for delay analysis





Delay Resolution Function of Bandwidth Synthesis



Legacy mode Geodetic VLBI

Freq.= 8212.99, 8252.99, 8352.99, 8512.99, 8732.99, 8852.99, 8912.99, 8932.99 MHz

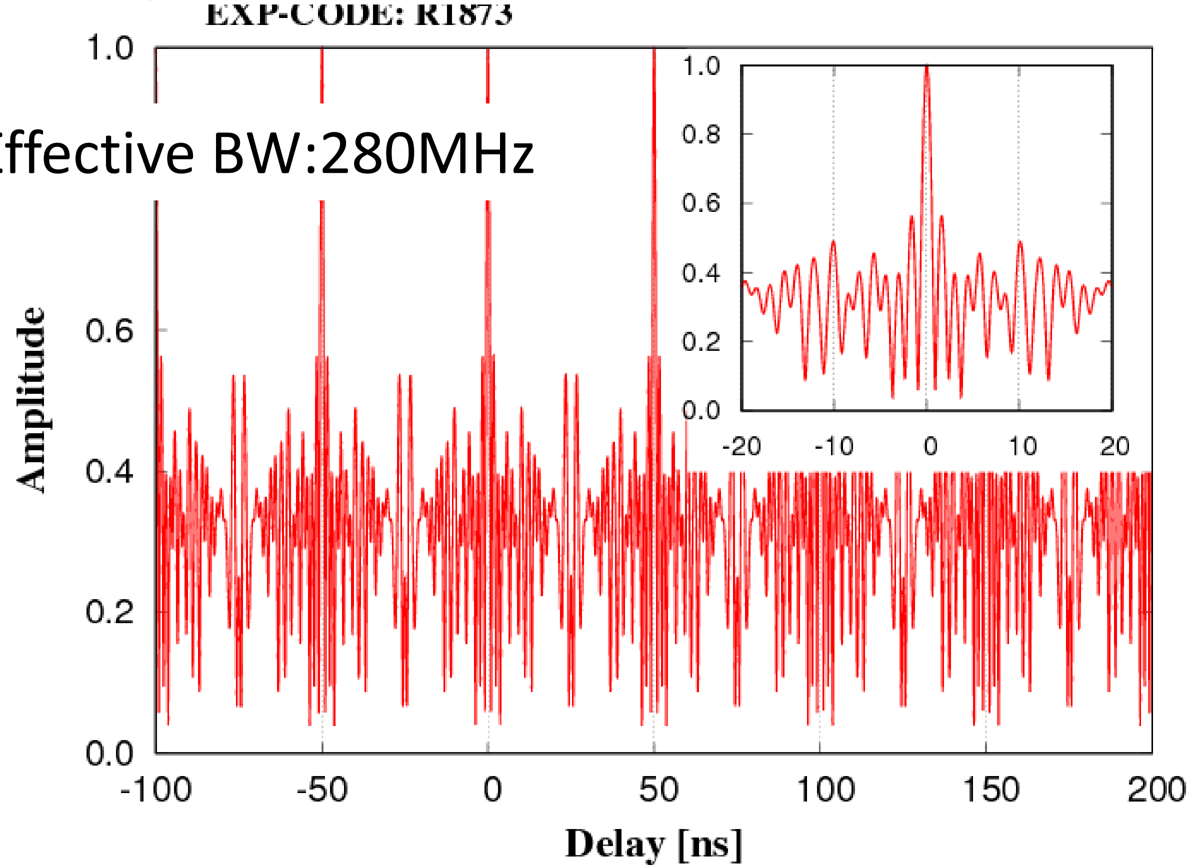
BW = 8MHz

Broadband VLBI

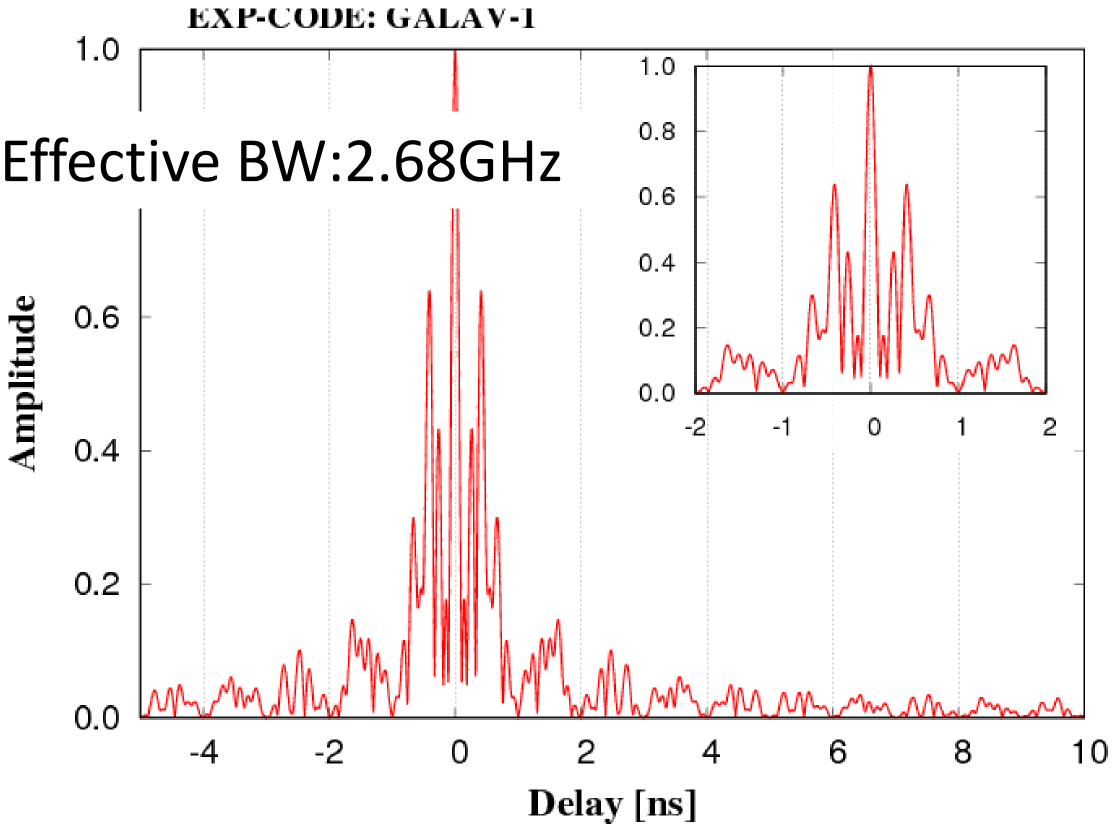
Freq.= 6000, 8500, 10800, 13300 MHz, BW= 1024MHz

- **10 times high resolution**
- **Ambiguity free**

Effective BW:280MHz

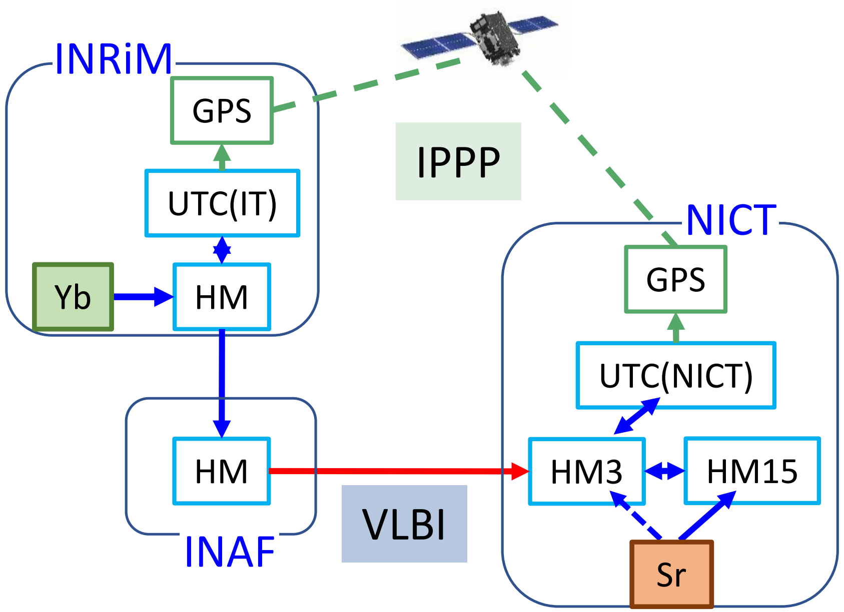


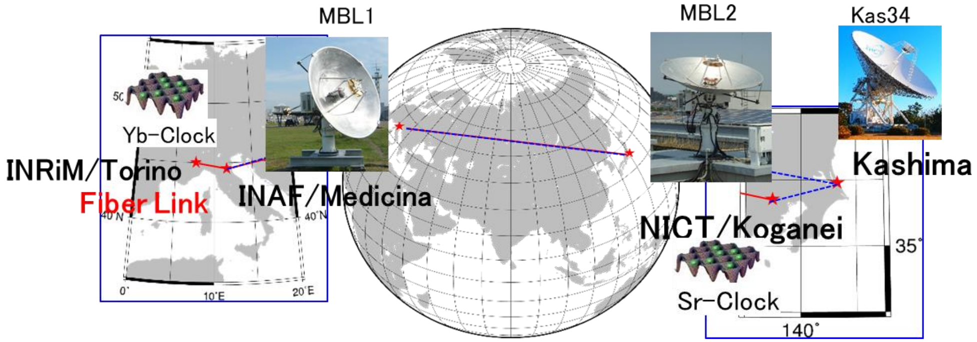
Effective BW:2.68GHz



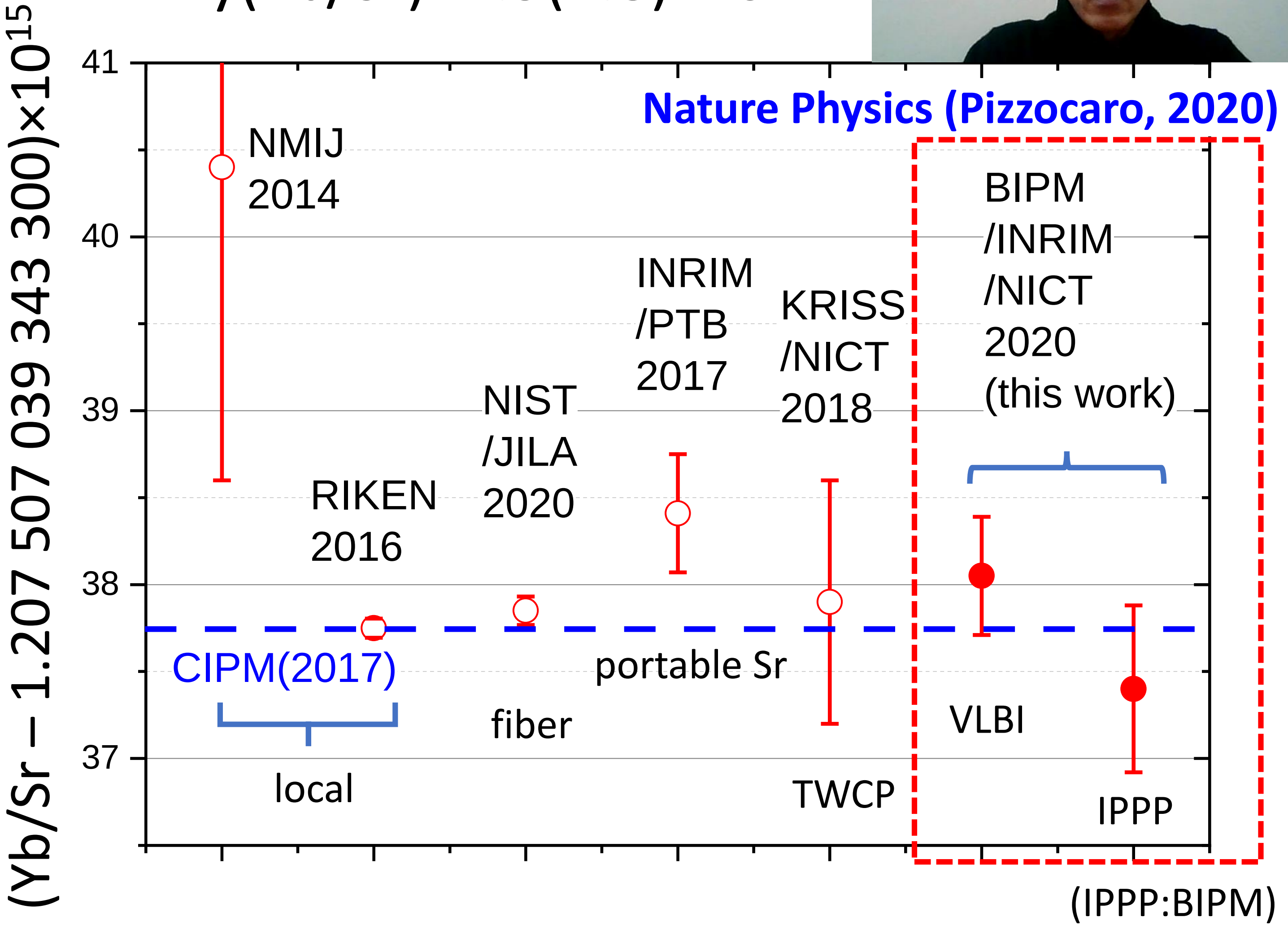
Yb/Sr Freq. Link: Comparison

Best precision for 9000 km distance



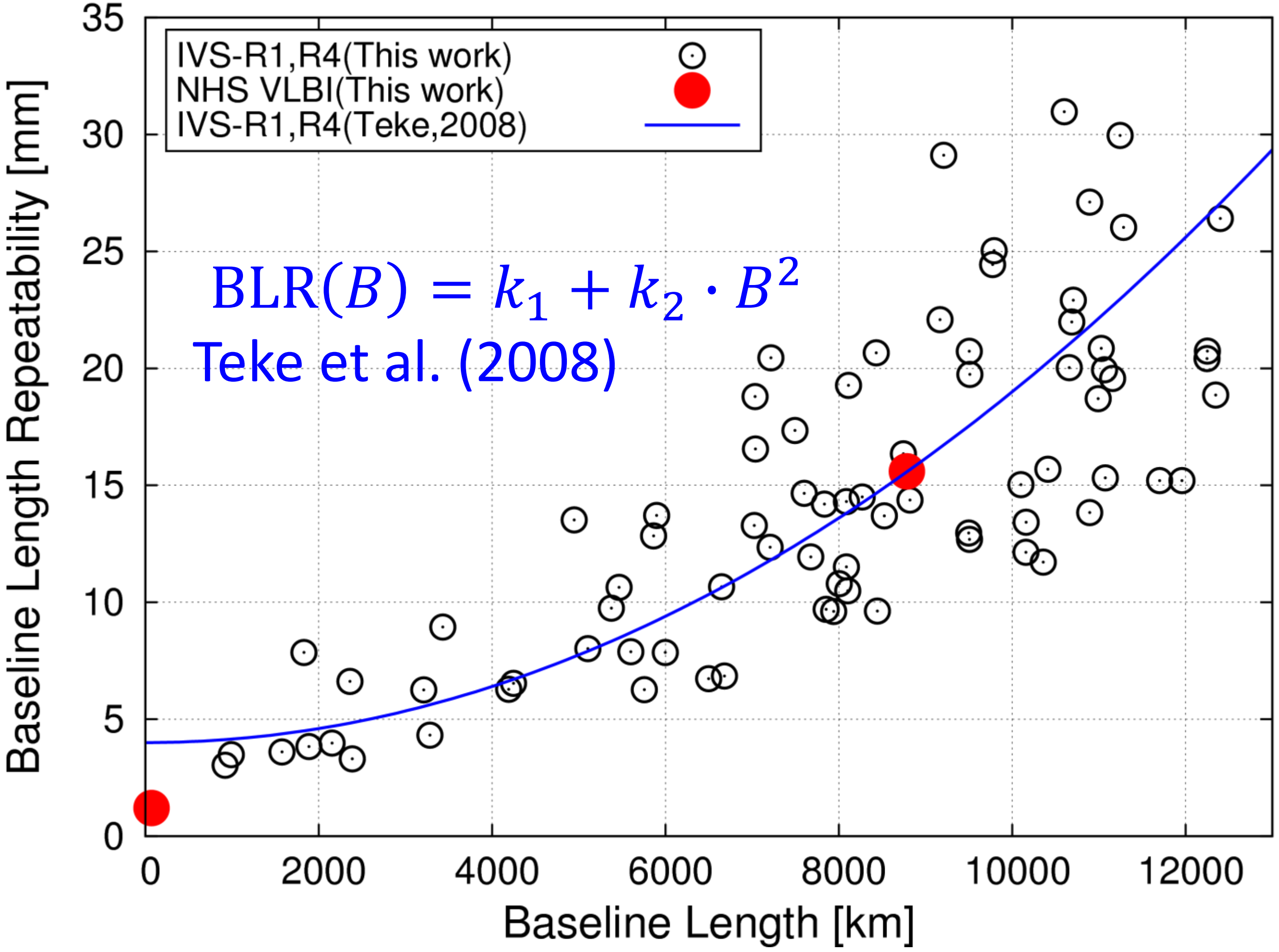


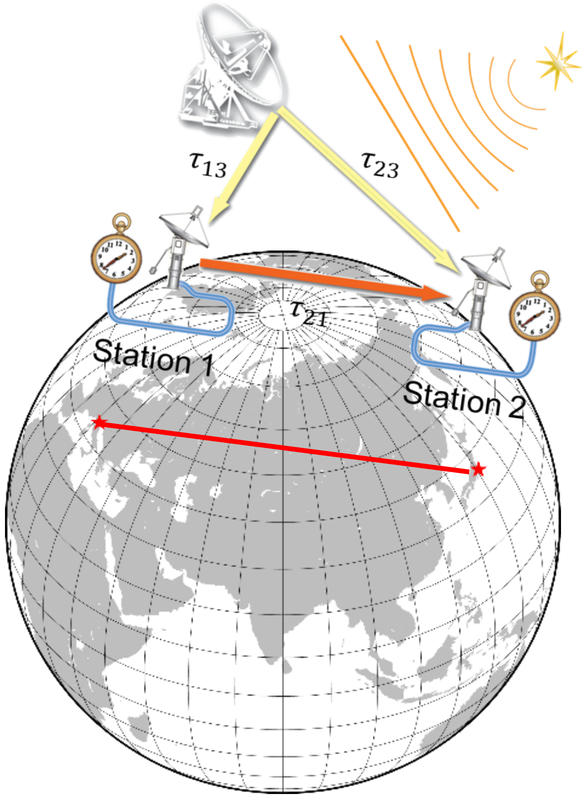
$y(Yb/Sr)=2.5(2.8)\times10^{-16}$



Baseline Length Repeatability (BLR)

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





Submitted to J. of Geodesy

Uncertainty Budget of our Broadband VLBI (SNR, Instrument)

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

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) 5K 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

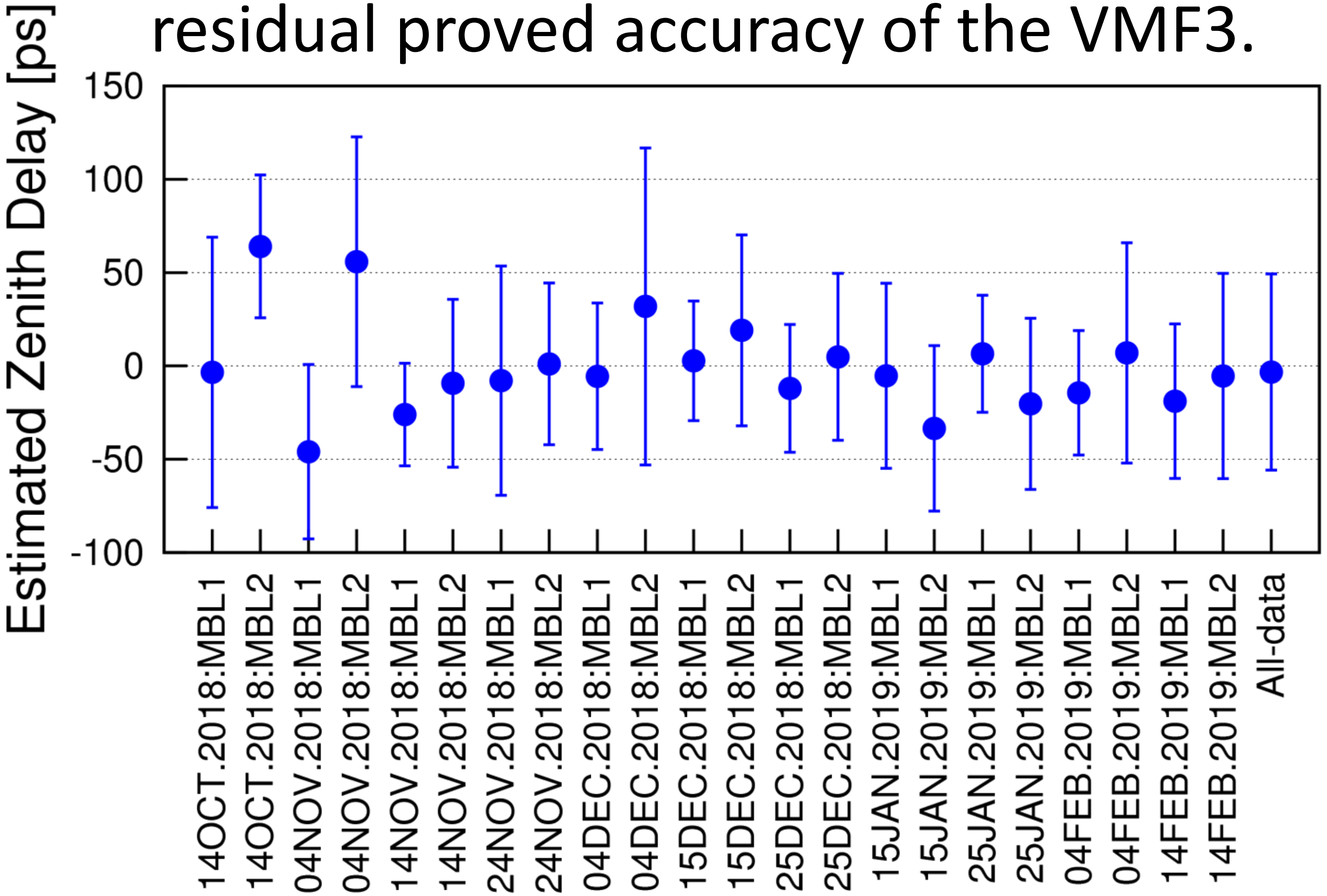
$$\sqrt{7.6^2 + 1.9^2 + 10^2 + 0.2^2 + 0.5^2} = 12.7\ \mathrm{ps}$$

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 our Broadband VLBI (Atmosphere)

VMF3 Dry, Wet and Grad. applied as a priori.

Zero avg. of estimated zenith atm. delay residual proved accuracy of the VMF3.

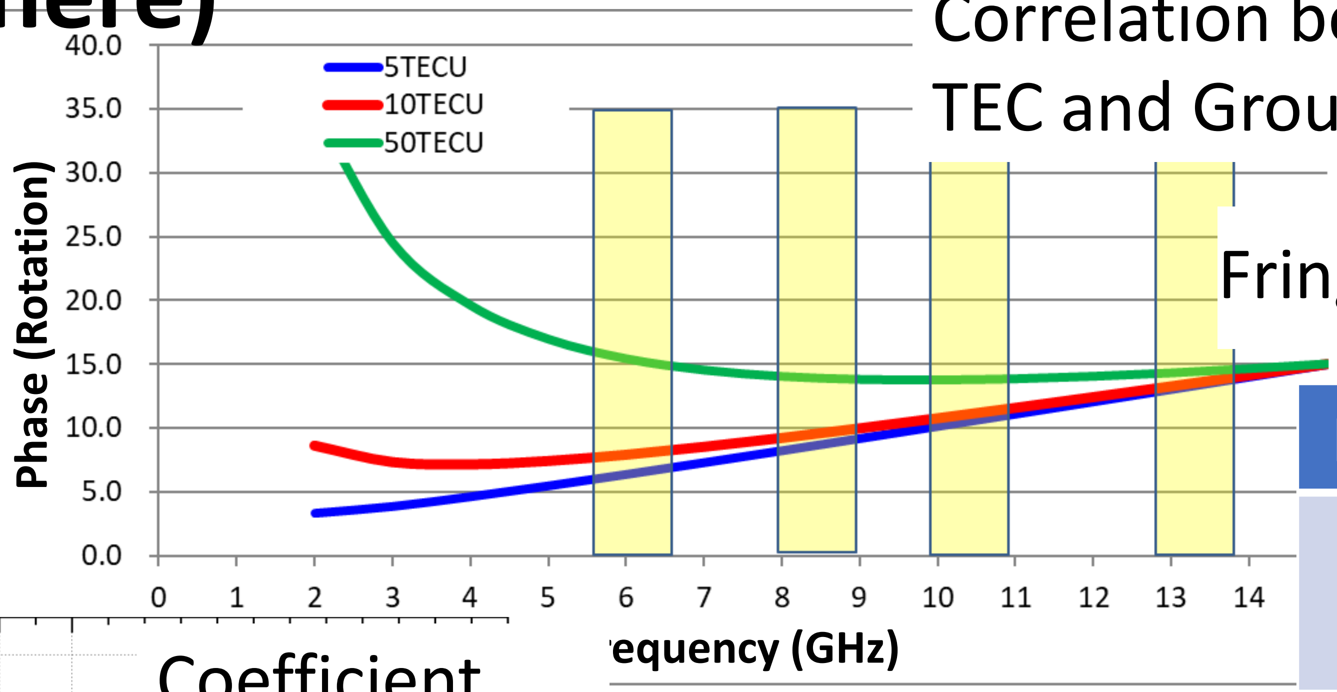


The VMF3 (Vienna Mapping Function)
Based on ECMWF(European Centre for Medium-Range Weather Forecasts) numerical weather model

- Dry, Wet, and Gradient every 6hours.

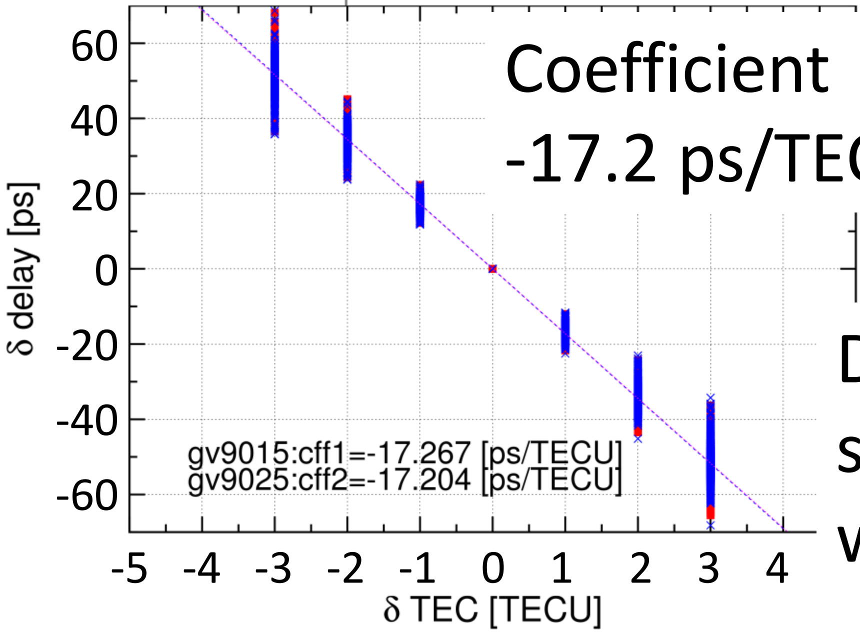
Error Source	uncertainty
Sensitivity (∝1/SNR)	6.4 ps
Instrumental	12.7 ps
Atmosphere	7.9 ps
Ionosphere	1.7～17 ps
Radio Source Structure	22-33 ps

Uncertainty Budget of Broadband VLBI (Ionosphere)



Correlation between TEC and Group Delay

Fringe Phase$= A\frac{\mathbf{TEC}}{f}$



Coefficient -17.2 ps/TECU

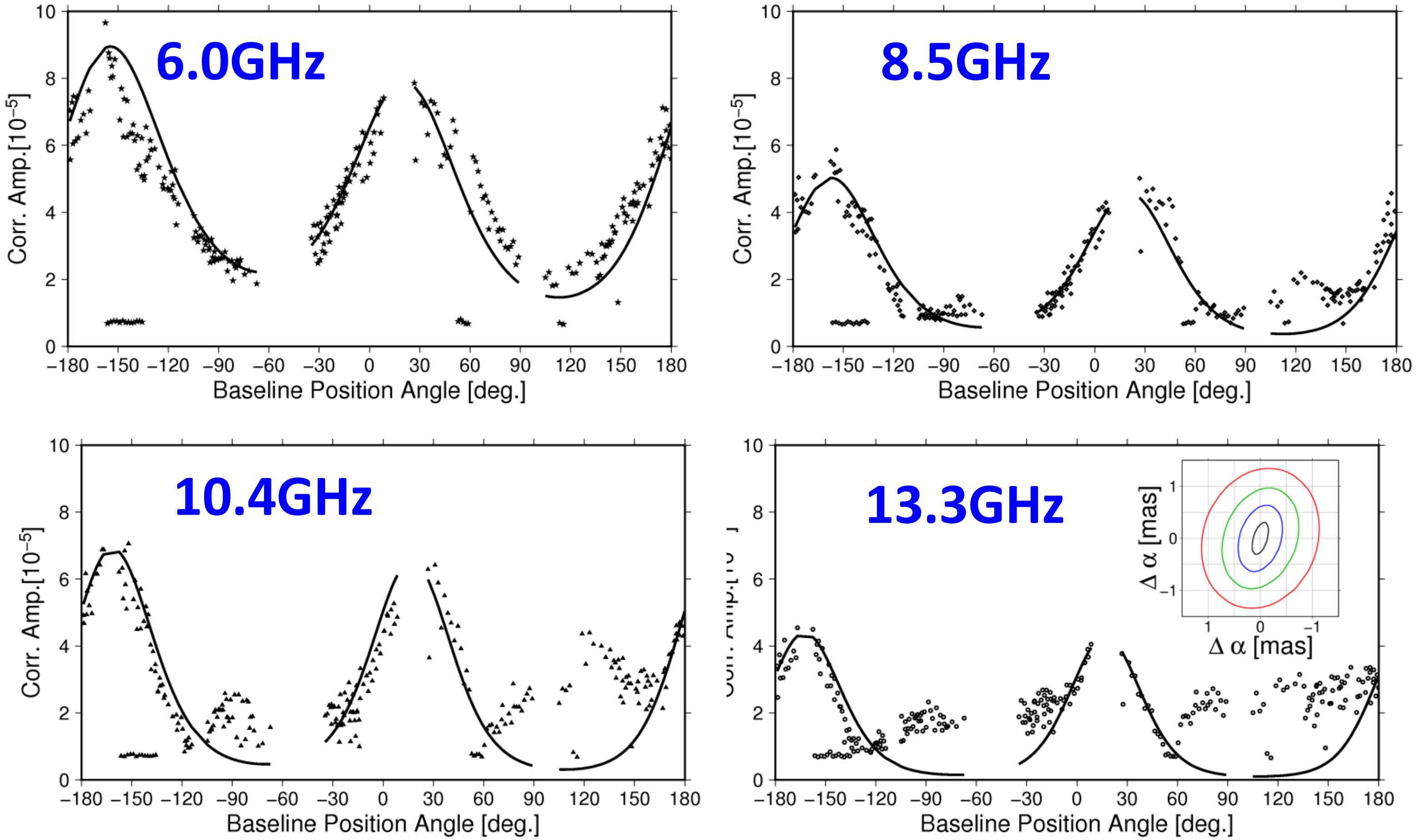
Due to limited SNR of small antenna, TEC error was 0.1-1TECU.

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 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

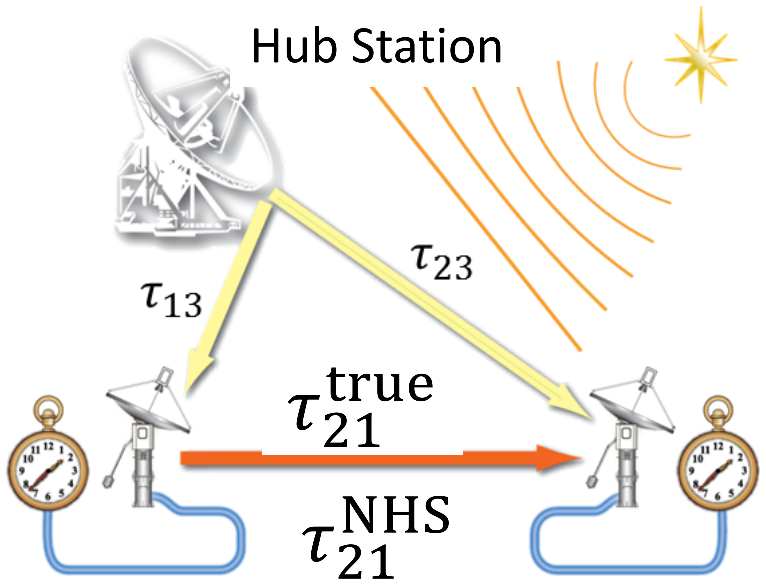


Error Source	uncertainty
Sensitivity (∝1/SNR)	6.4 ps
Instrumental	12.7 ps
Atmosphere	7.9 ps
Ionosphere	1.7～17 ps
Radio Source Structure	22-33 ps

Potential of Node-Hub Style (NHS) VLBI to reduce radio source structure effect

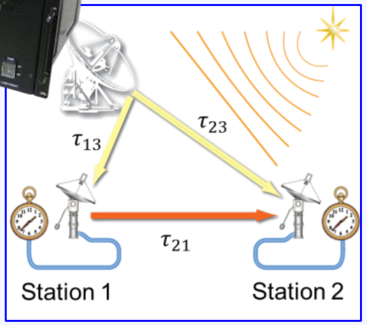
$$\tau_{21}^{NHS} - \tau_{21}^{true} = (\tau_{31}^{str} + \tau_{23}^{str}) - \tau_{21}^{str}.$$

HNS VLBI has smaller structure effect than real baseline because generally $(\boldsymbol{\tau_{31}^{str}} + \boldsymbol{\tau_{23}^{str}}) \leq \boldsymbol{\tau_{21}^{str}}$



Summary

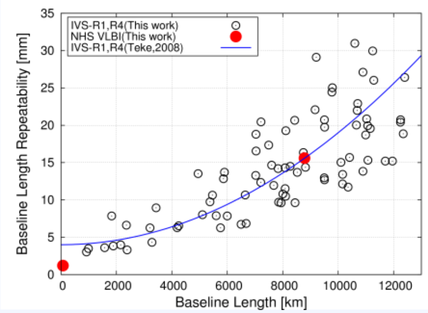
Development: Broadband VLBI system(Feed, RF Direct-Sampling) and transportable VLBI with Node-Hub Style scheme.



Achievement: Baseline length repeatability (BLR) was comparable with IVS-R1,R4 sessions.

Freq. link of Yb/Sr optical clock was made about 2.8×10^{-16} uncertainty on 9000km .

Nature physics (Pizzocaro,2020)



Error Evaluation: Dominating 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

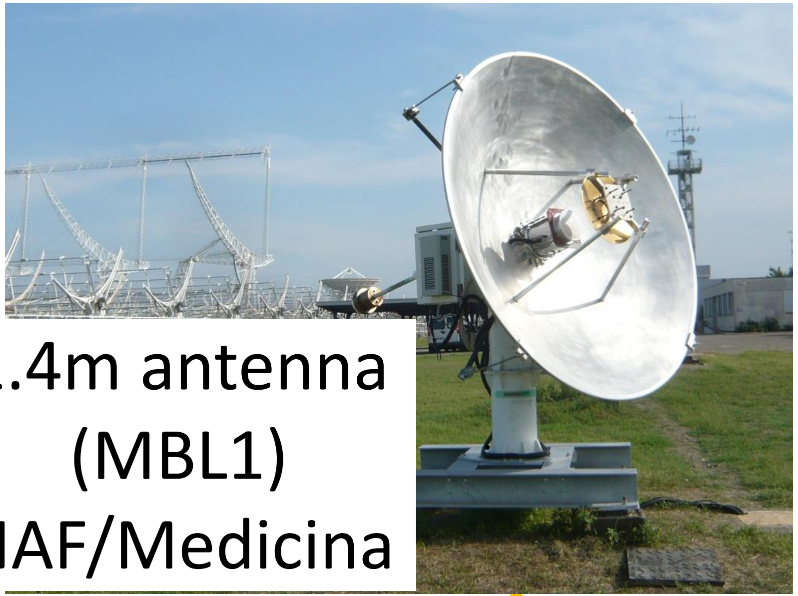
Submitted to J. of Geodesy

Thank you for your Attention

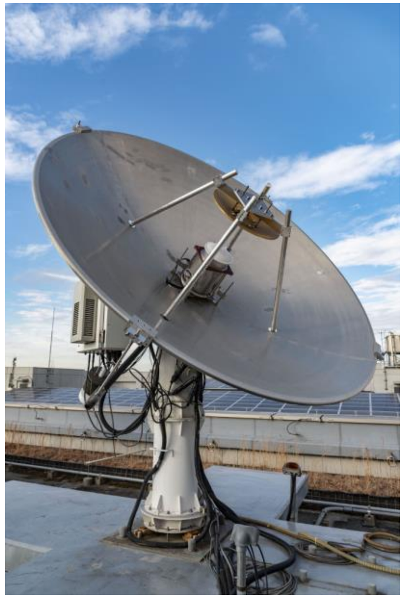
Acknowledgements

- G.Cerretto, F.Bregolin, F.Levi, A.Mura, E.Cantoni, P.Barbieri, A.Tampellini of INRiM, Y.Miyauchi, S.Hasegwa, H.Ishijima of NICT, T.Suzuyama, K.Watabe of NMIJ, Y.Fukuzaki, T.Wakasugi, S.Kurihara, Y.Umei, H.Ueshiba, S.Matsumoto of GSI for contribution to this work.
- High speed research network environment is supported by JGN,GARR, GEANT, Internet2, and TransPAC. Special thanks to T.Ikeda of KDDI. High speed data transfer software JIVE5ab developed by H.Verkouter of JIVE.
- VLBI observation is supported by analysis software **Calc/Solve**, antenna control software **Field System9**, and scheduling software **Sked**, all developed by NASA/GSFC.

Three Broadband VLBI Stations

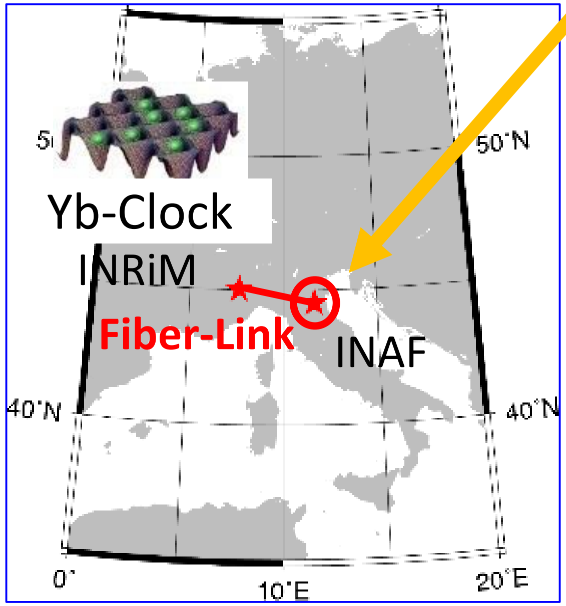


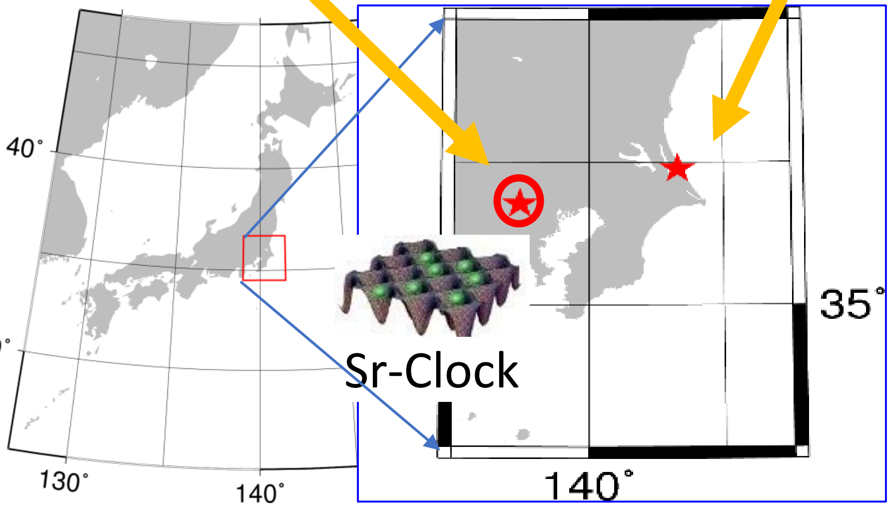
2.4m antenna
(MBL1)
INAF/Medicina



2.4m antenna
(MBL2)
NICT/Koganei

34m Diameter





NICT/Ka