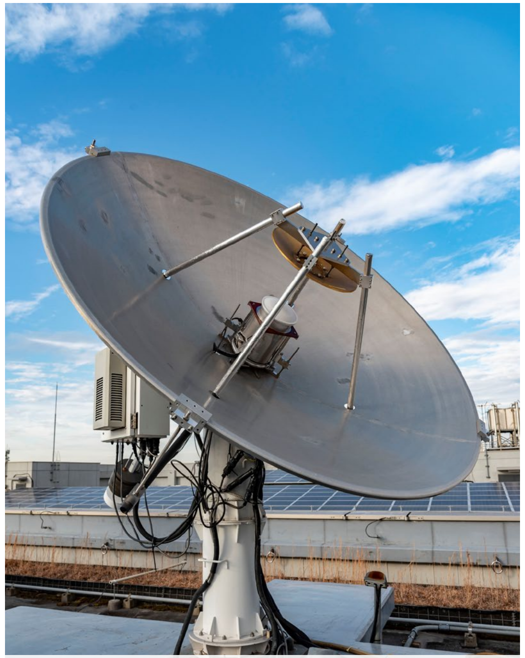
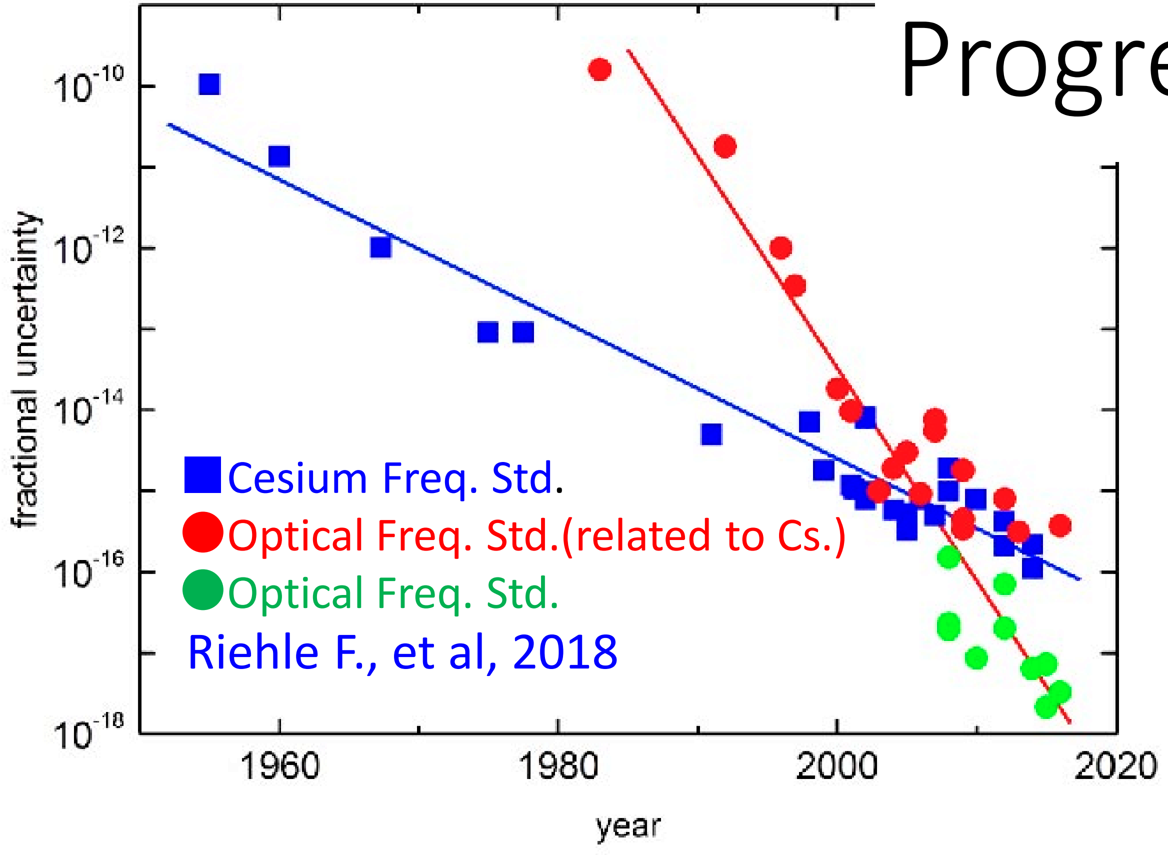
Broadband VLBI experiments with transportable stations between Italy – Japan



M.Sekido, K.Takefuji, H.Ujihara, T.Kondo, M.Tsutsumi, E.Kawai, H.Hachisu, 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, J.Leute, G.Petit, Davide Calonico, Tetsuya Ido

EAVN workshop 4 Mar. 2020

Progress of Optical Freq. Std.



- Uncertainty of optical freq. std reaches in order of 10^{-18}.
- Inter comparison between optical frequency standards is required.

Secondary Representation of Second

Table 2. SRS as of 2017.

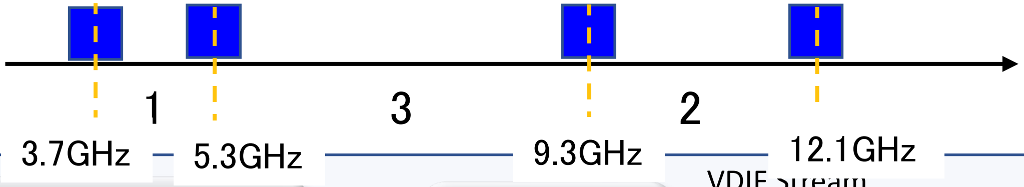
Frequency (Hz)	Fractional uncertainty	Transition
6834682610.9043126	6×10^{-16}	^{87}Rb ground state hfs
429228004229873.0	4×10^{-16}	^{87}Sr neutral atom, $5s^2\ ^1S_0$–$5s5p\ ^3P_0$
444779044095486.5	1.5×10^{-15}	^{88}Sr$^+$ ion, $5s\ ^2S_{1/2}$–$4d\ ^2D_{5/2}$
518295836590863.6	5×10^{-16}	^{171}Yb neutral atom, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$
642121496772645.0	6×10^{-16}	^{171}Yb$^+$ ion, $^2S_{1/2}$–$^2F_{7/2}$
688358979309308.3	6×10^{-16}	^{171}Yb$^+$ ion, $6s\ ^2S_{1/2}$–$5d\ ^2D_{3/2}$
1064721609899145.3	1.9×10^{-15}	^{199}Hg$^+$ ion, $5d^{10}6s\ ^2S_{1/2}$–$5d^96s^2\ ^2D_{5/2}$
1121015393207857.3	1.9×10^{-15}	^{27}Al$^+$ ion, $3s^2\ ^1S_0$–$3s3p\ ^3P_0$
1128575290808154.4	5×10^{-16}	^{199}Hg neutral atom, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$

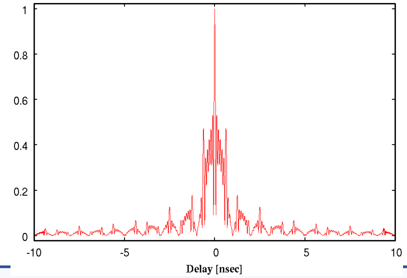
Riehle F., et al, 2018

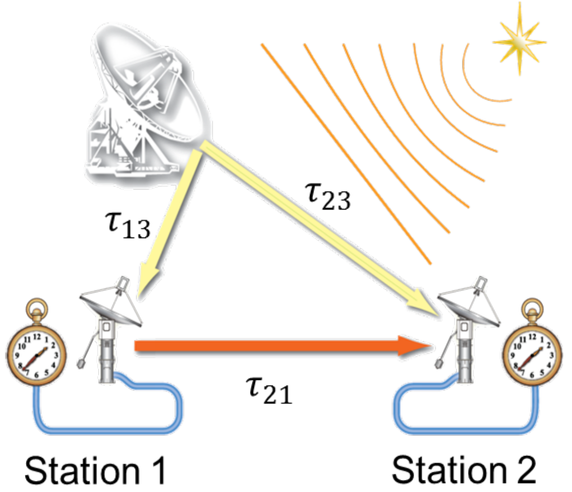
Project Overview

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

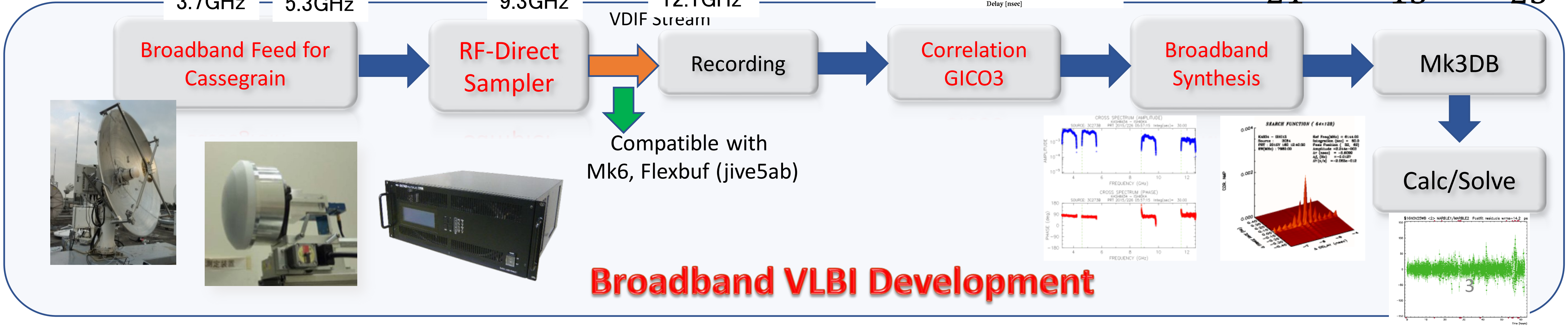
- ■Broad Radio Frequency：3.2-14 GHz (Almost VGOS compatible)
- ■Transportable Station: Node-Hub Style VLBI
- ■High data-rate acquisition： 4 band (1024MHz width/band)
  - ■Effective Bandwidth：3.3GHz (10 times wider than conventional）
  - ■Absolute delay :Free from ambiguity



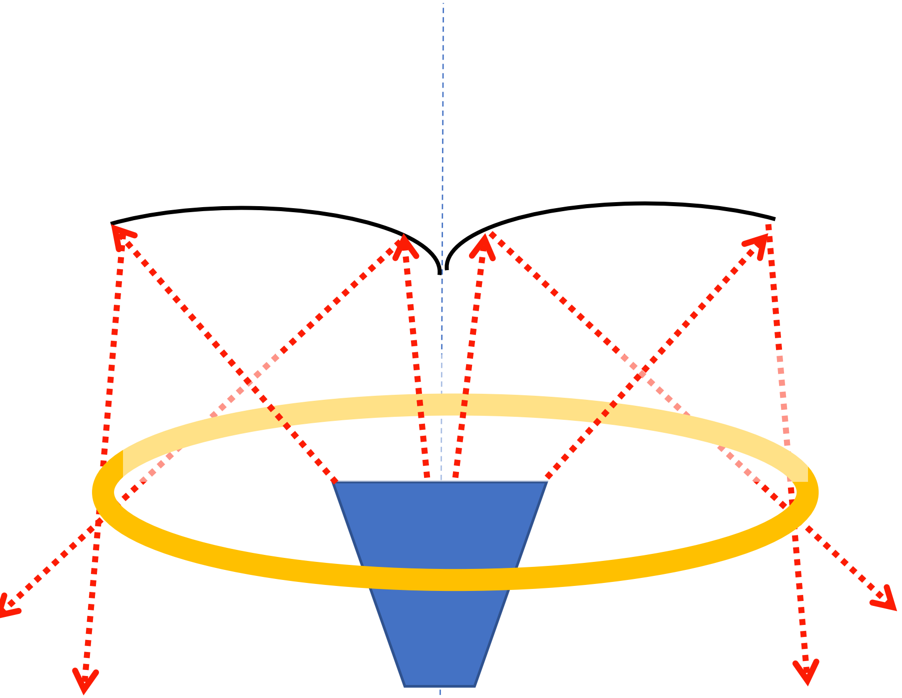




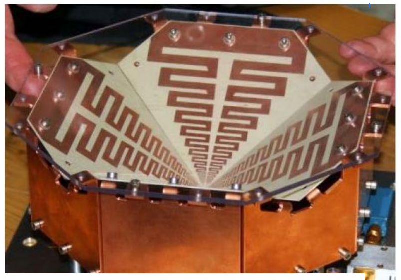
$$\tau_{21} = \tau_{13} - \tau_{23}$$



Reason why NICT Developed own Broadband Feeds



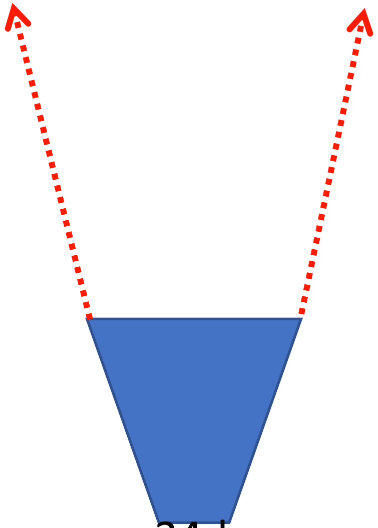
～120deg.



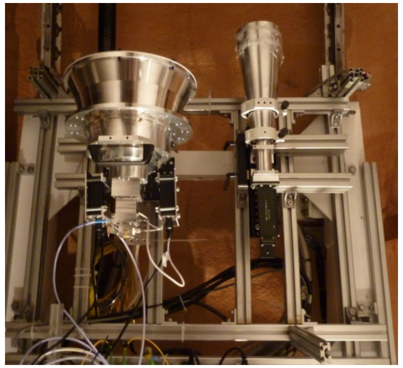
Eleven Feed

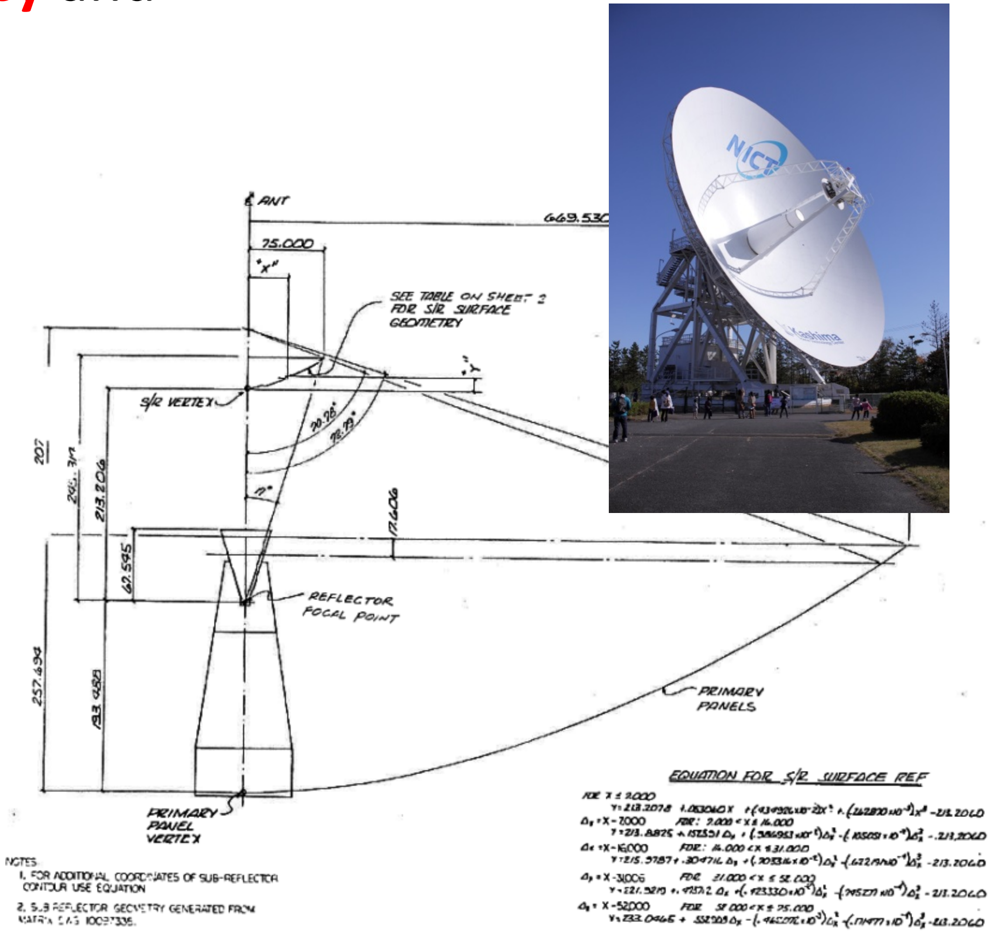
QRFH

Requirement of
Broadband Frequency and
Narrow beam width



～34deg.





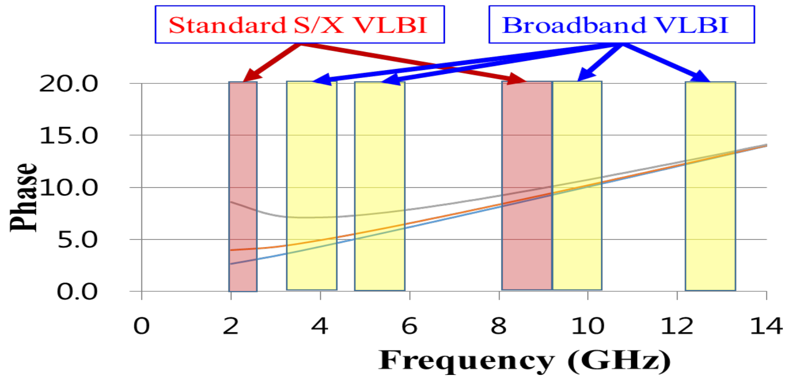
Broadband Feed and RF-Direct Sampling

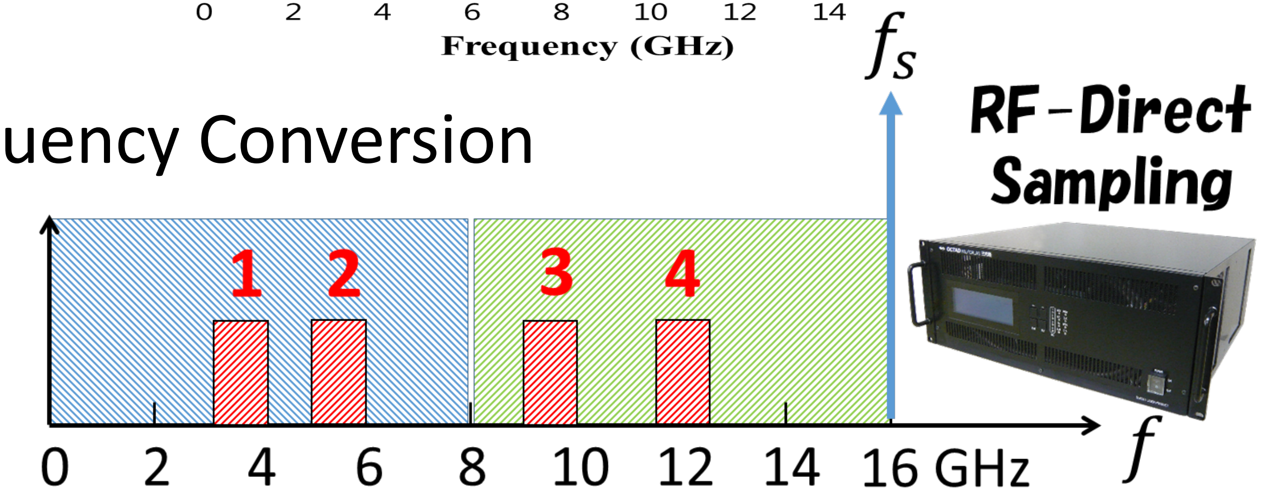
- Broadband VLBI, 3-14 GHz range

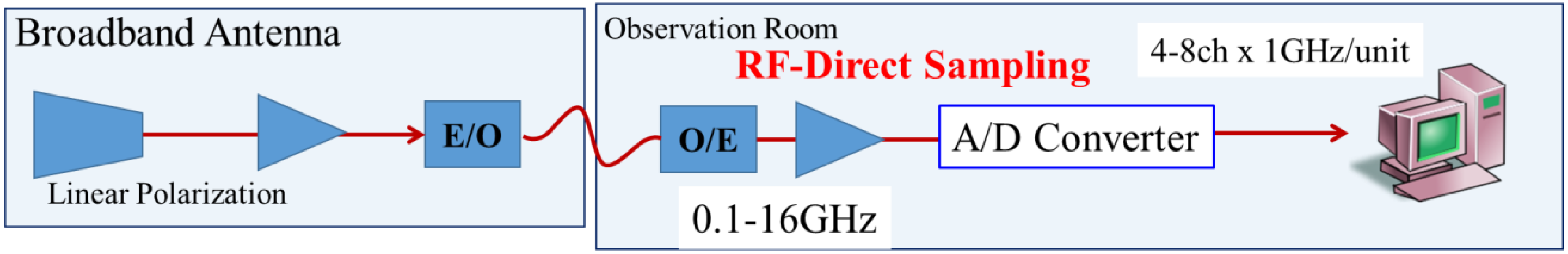
  One order large bandwidth

  → one order fine delay precision.

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







A Novel features of this system

Node-Hub Style (using closure delay)

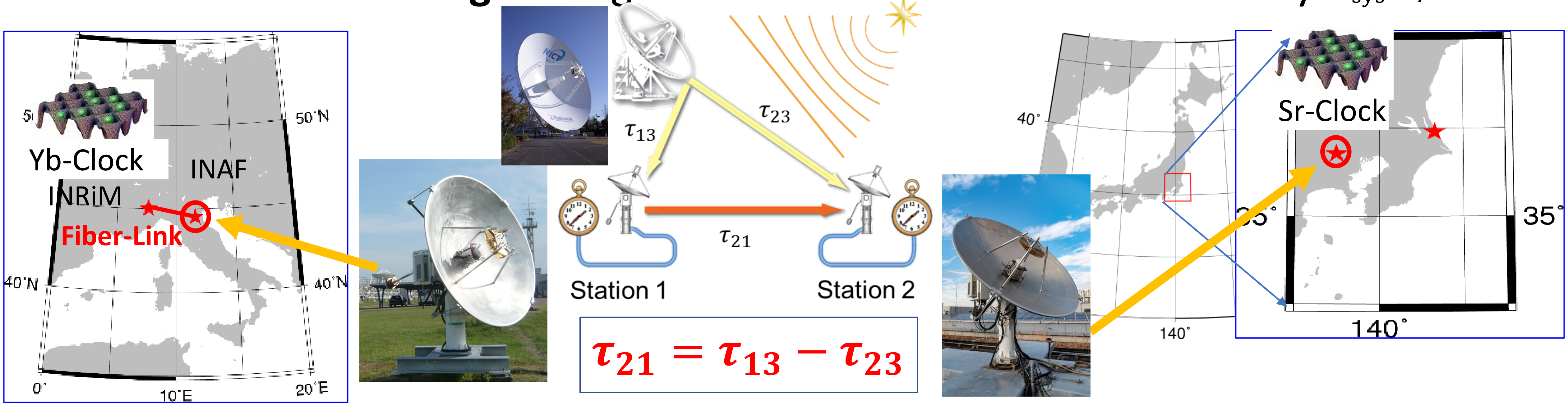
$$\tau_{21}^{NHS}(t_1) = \tau_{23}(t_1) - \tau_{13}(t_1) + \tau_{13}(t_1)\dot{\tau}_{21}(t_1)$$

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

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

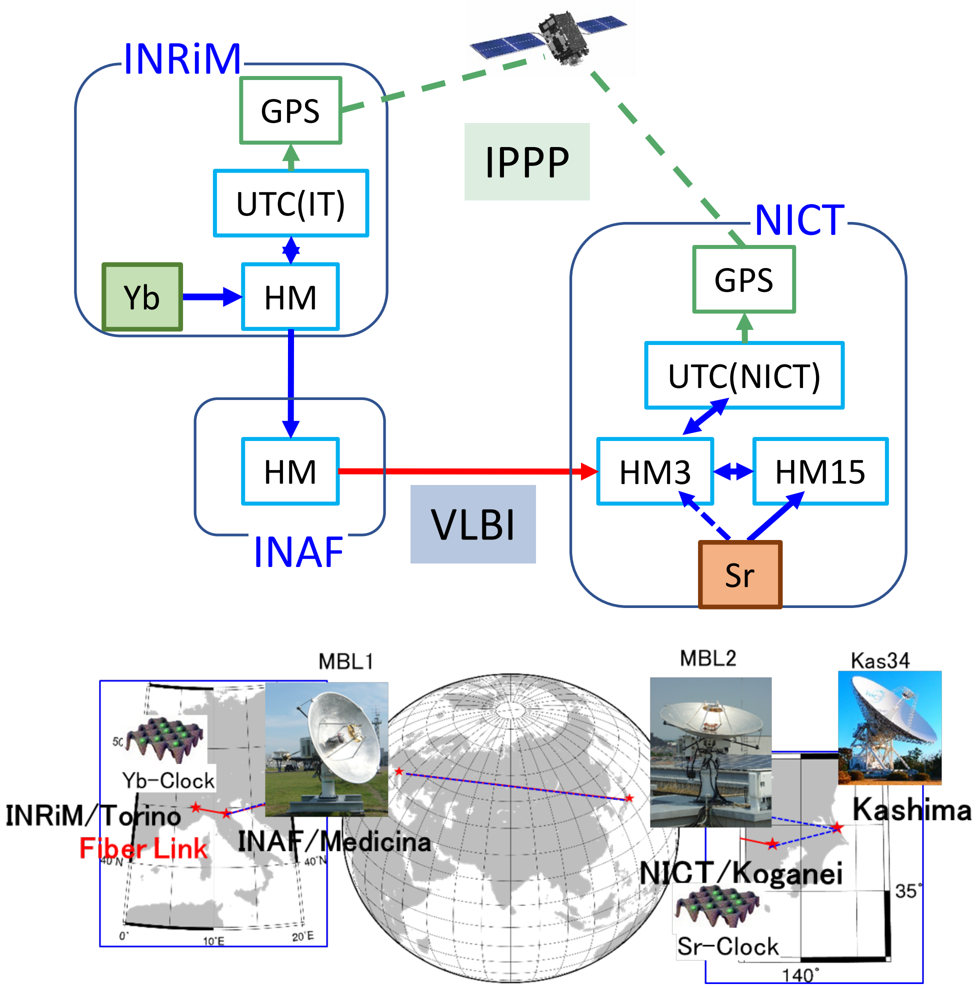
D_n : Diameter
S : Radio Flux
η_n : Efficiency
T_{sys}: System noise.

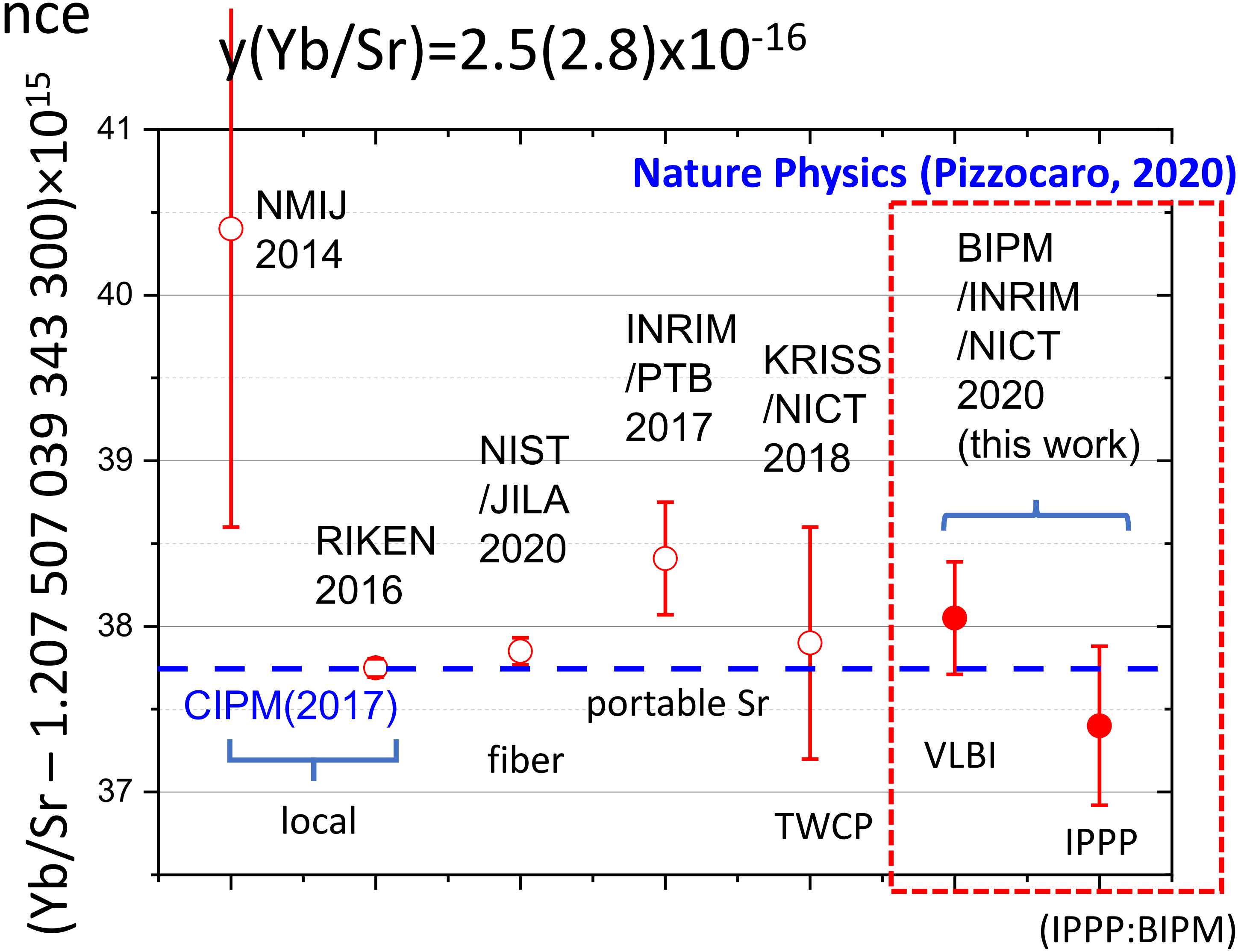
- **Cancel effect:** Large station(Grav. Deformation, Cable delay)
- **Easy deployment**(Small antenna): low-cost, transportable
- **Potential advantage:** mitigation of radio source structure delay



Yb/Sr Freq. Link: Comparison

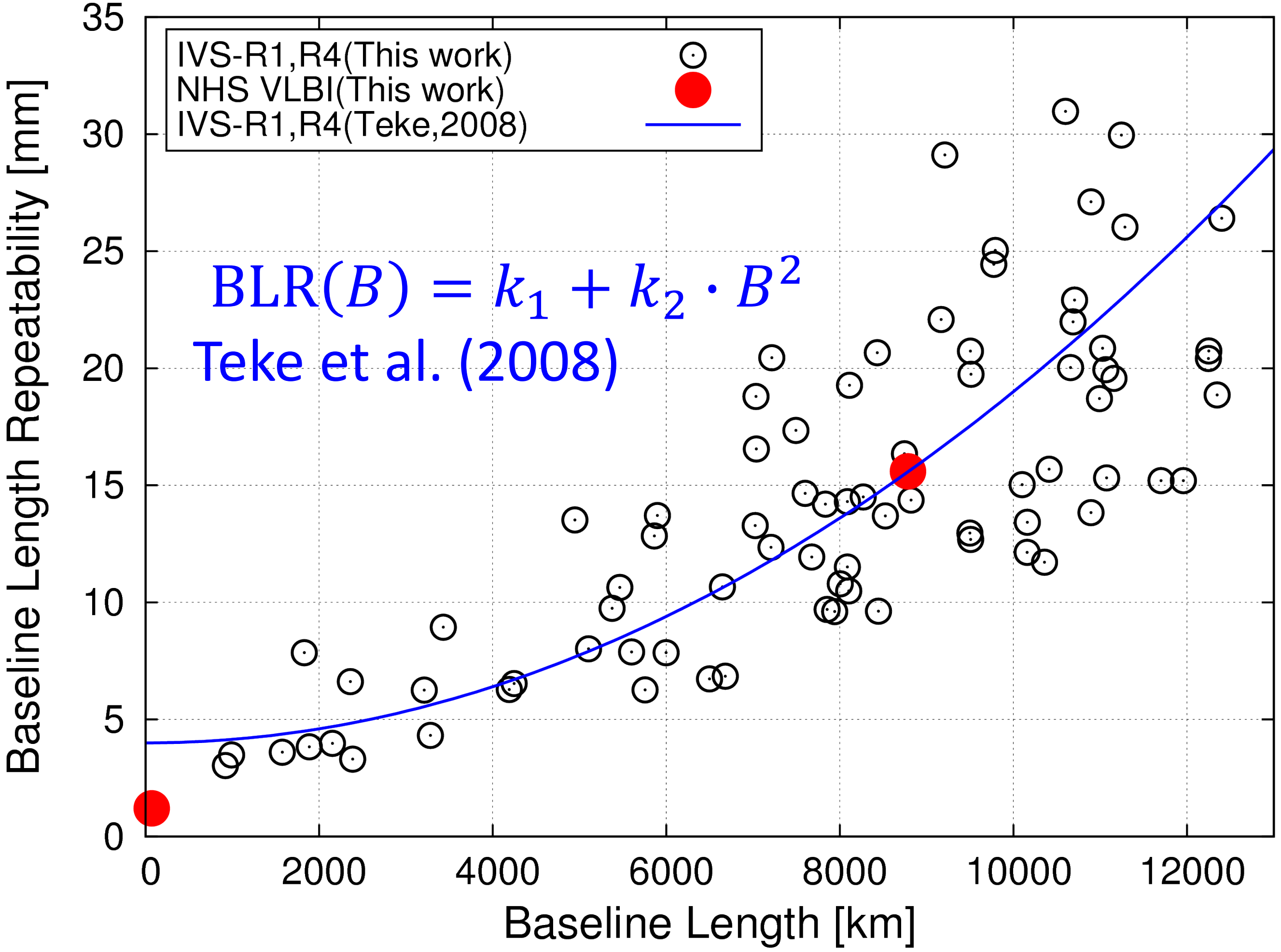
Best precision for 9000 km distance

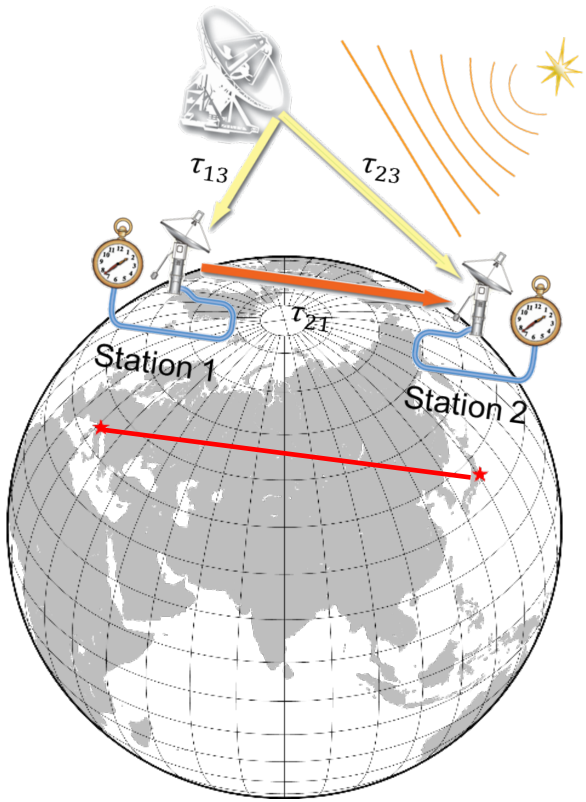




Baseline Length Repeatability (BLR)

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





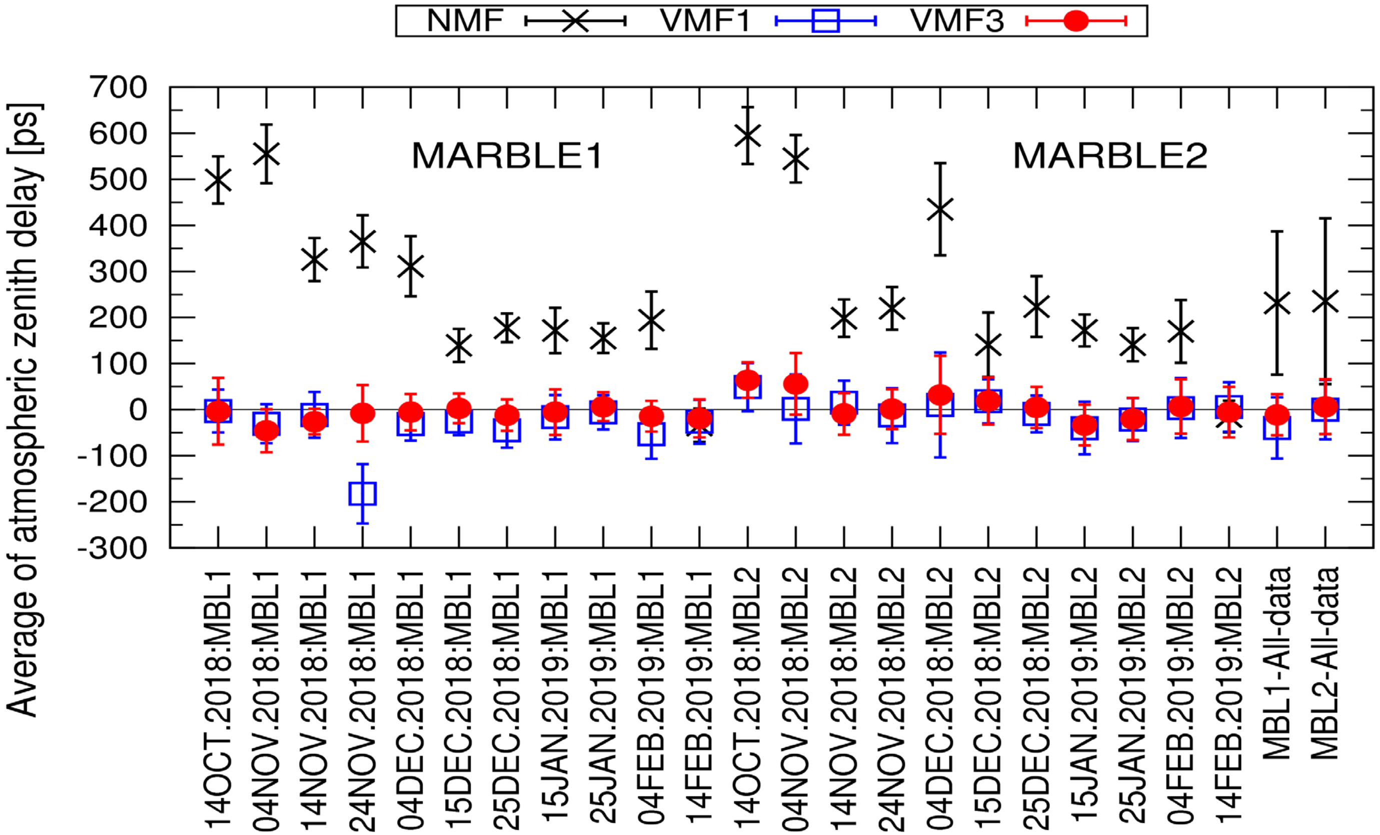
Submitted to J. of Geodesy

Uncertainty Budget of our Broadband VLBI (Atmosphere)

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

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)

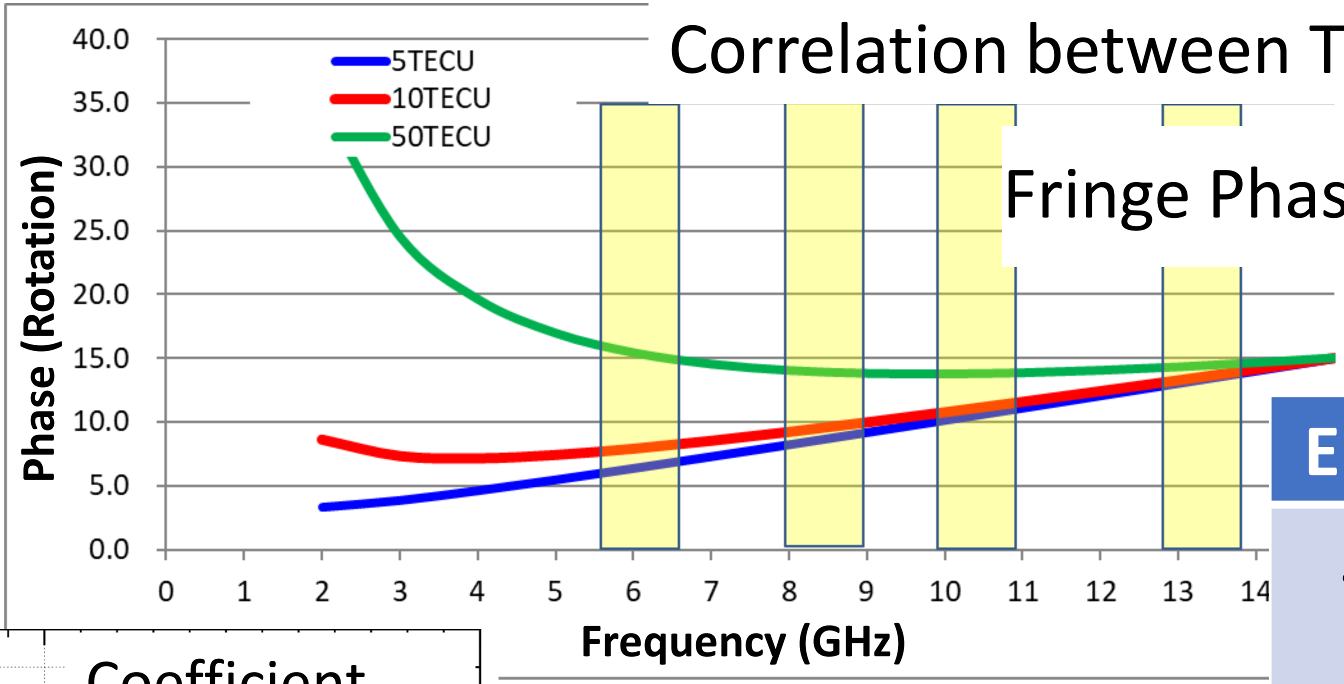
Based on ECMWF(European Centre for Medium-Range Weather Forecasts) numerical weather model

- Dry, Wet, and Gradient every 6hours.

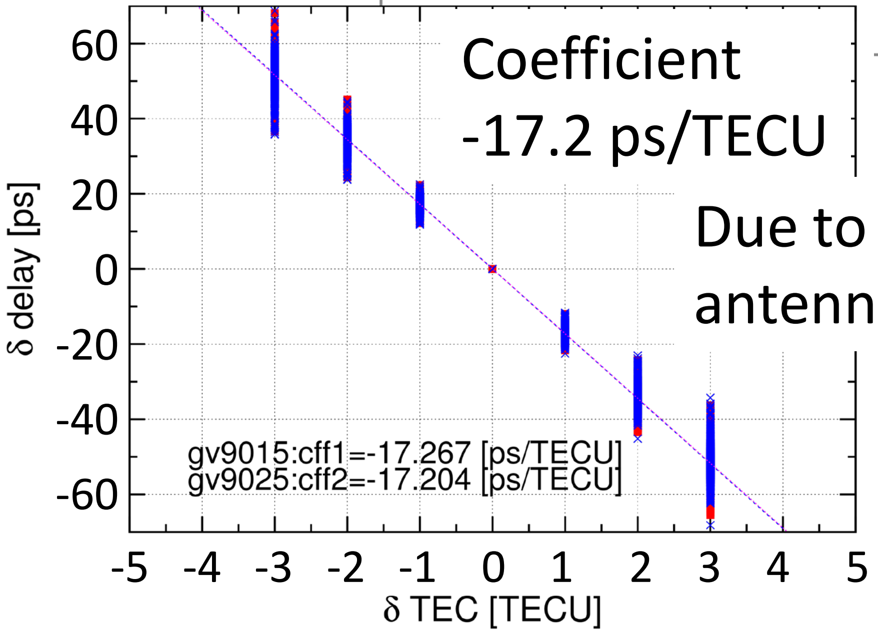
Error Source	uncertainty
Sensitivity (∝1/SNR)	6.4 ps
Instrumental	12.7 ps
Atmosphere	7.9 ps
Ionosphere	1.7～17 ps
Radio Source Structure	22-33 ps

Uncertainty Budget of Broadband VLBI (Ionosphere)

Correlation between TEC and Group Delay



$$\text{Fringe Phase} = 2\pi\tau_g \cdot f + A\frac{\text{TEC}}{f}$$



Coefficient
-17.2 ps/TECU

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

Total Electron Content (TEC) is column density of electrons in the line of sight.
1 TECU $=10^{16}$ electrons/m^2

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Sensitivity (∝1/SNR)	6.4 ps
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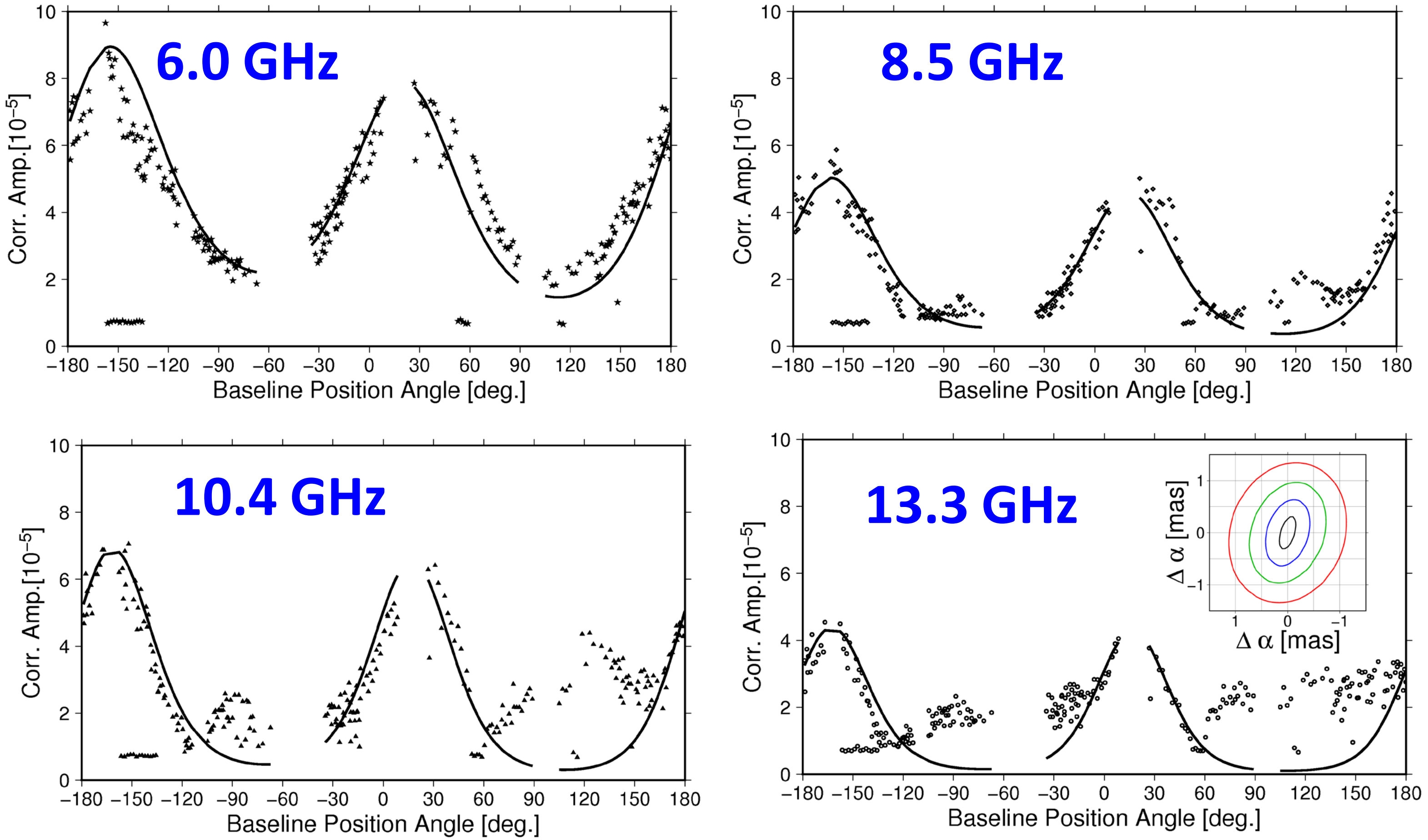
Radio Source Structure	22-33 ps

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**.

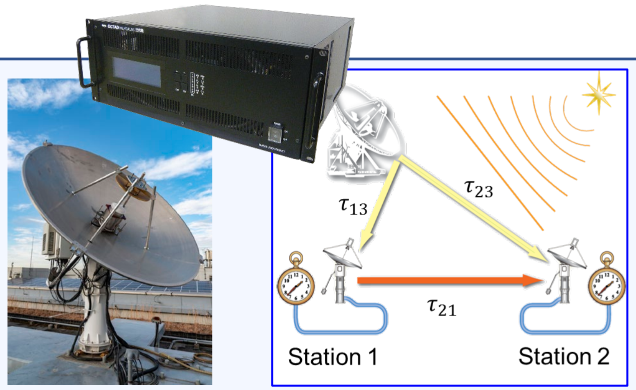
Radio Source:1928+738



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

Summary

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

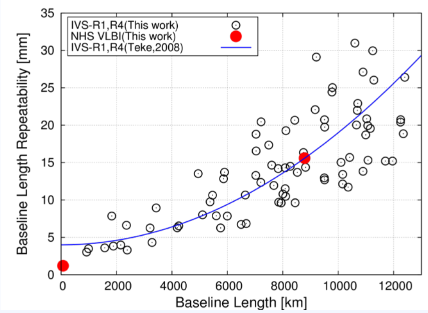


Achievement: Baseline length repeatability (BLR) was comparable with IVS-R1,R4 sessions.

Accepted at J. of Geodesy

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

Nature physics (Pizzocaro,2020)



Acknowledgements

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- 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.