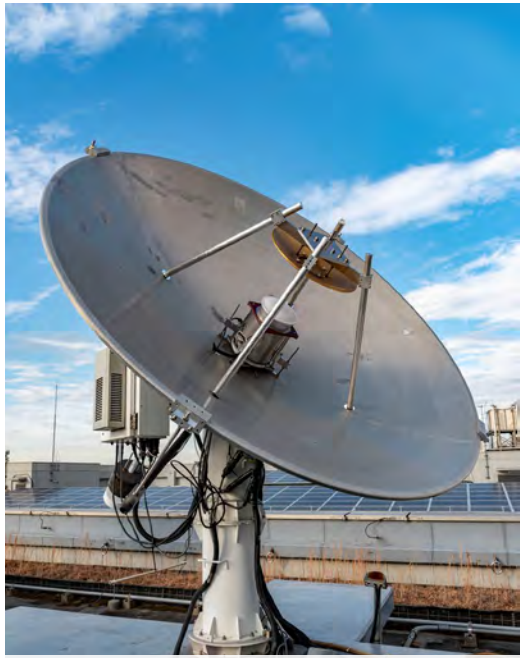
A Broadband VLBI system with transportable stations
- A tool for high accurate frequency transfer and for geodesy -

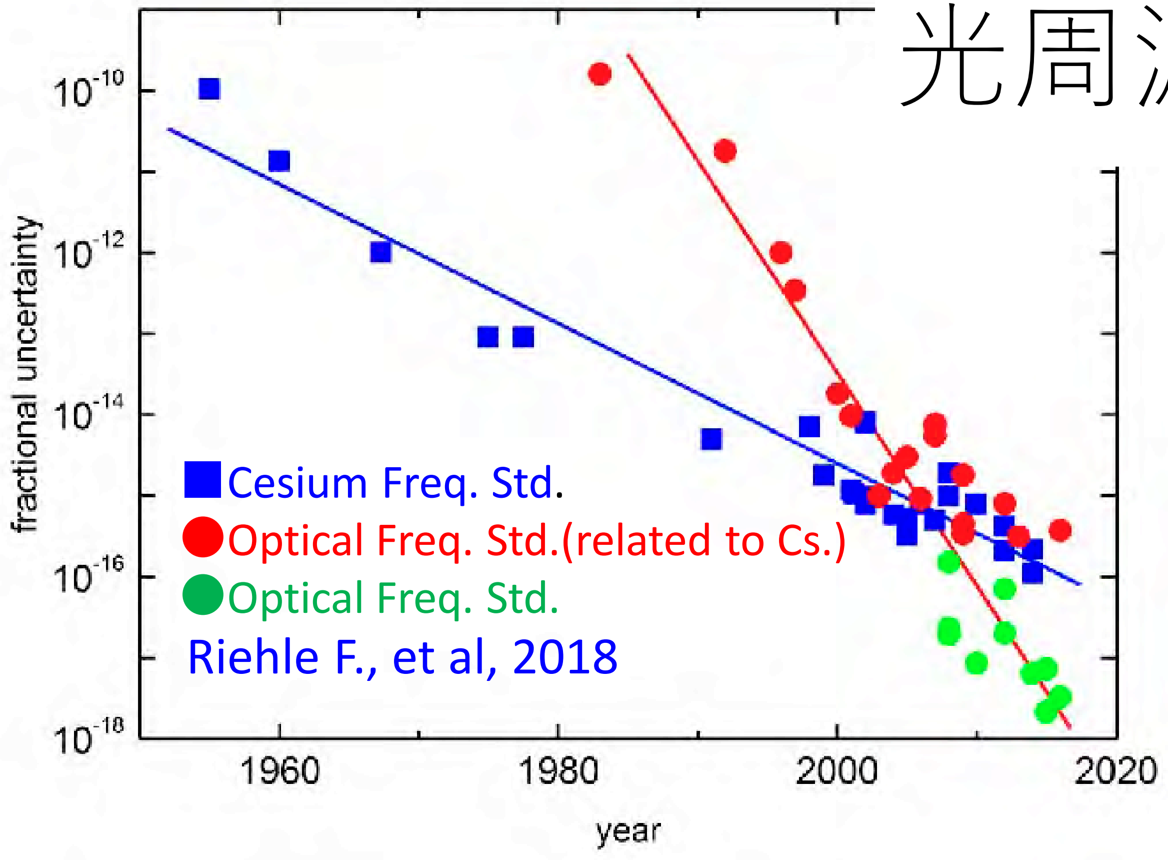



M.Sekido, K.Takefuji, H.Ujihara, T.Kondo, M.Tsutsumi, E.Kawai, H.Hachisu, N.Nemitz, M.Pizzocaro, C.Clivati, F.Perini, M.Negusini, G.Maccaferri, R.Ricci, M.Roma, C.Bortolotti, G.Zacchiiroli, J.Roda, K.Namba, J.Komuro, Y.Okamoto, R.Takahashi, R.Ichikawa, J.Leute, G.Petit, Davide Calonico, Tetsuya Ido

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

令和2年度　GGOS Japan報告会　2020年3月19日

光周波数標準技術の進展



- 光周波数標準の周波数不確かさがセシウム（マイクロ波）の不確かさを超えて 10^{-18}. の桁に達している。
- 「秒」の再定義が議題に上っており、光周波数標準機関の比較が必要。

Secondary Representation of Second

Table 2. SRS as of 2017.

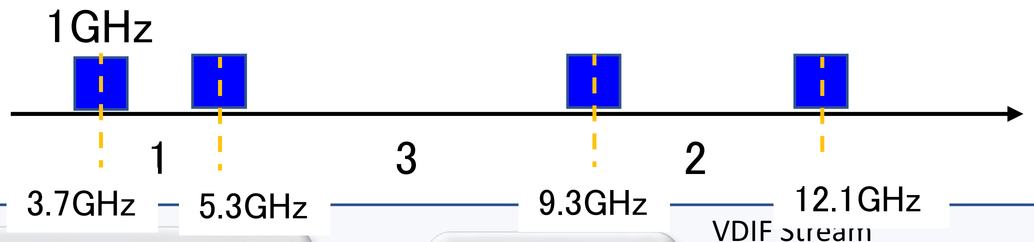
Frequency (Hz)	Fractional uncertainty	Transition
6834 682 610.904 3126	6×10^{-16}	^{87}Rb ground state hfs
429 228 004 229 873.0	4×10^{-16}	^{87}Sr neutral atom, $5s^2\ ^1S_0$–$5s5p\ ^3P_0$
444 779 044 095 486.5	1.5×10^{-15}	^{88}Sr$^+$ ion, $5s\ ^2S_{1/2}$–$4d\ ^2D_{5/2}$
518 295 836 590 863.6	5×10^{-16}	^{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, $6s^2\ ^1S_0$–$6s6p\ ^3P_0$

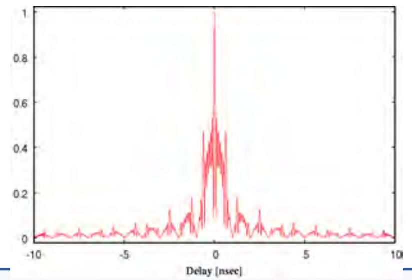
Riehle F., et al, 2018

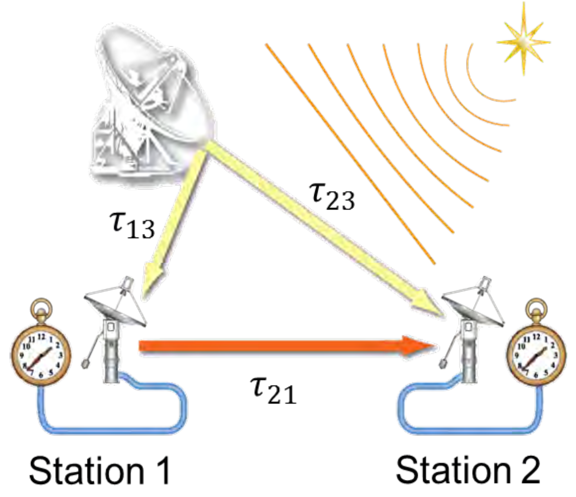
Project Overview

目的: SI単位の1秒の再定義に向けた、精密周波数比較

- ■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



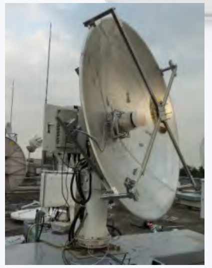


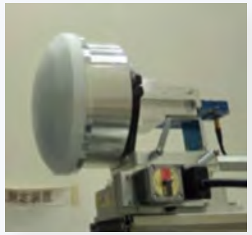


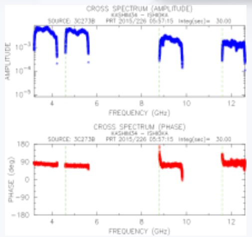
$$\tau_{21} = \tau_{13} - \tau_{23}$$

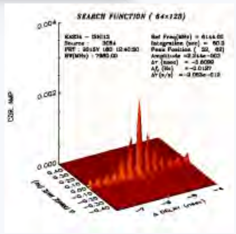
Broadband Feed for Cassegrain → RF-Direct Sampler → (VDIF Stream) Recording → Correlation GICO3 → Broadband Synthesis → Mk3DB → Calc/Solve

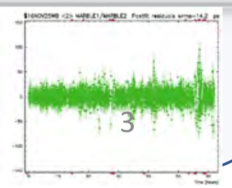
Compatible with Mk6, Flexbuf (jive5ab)





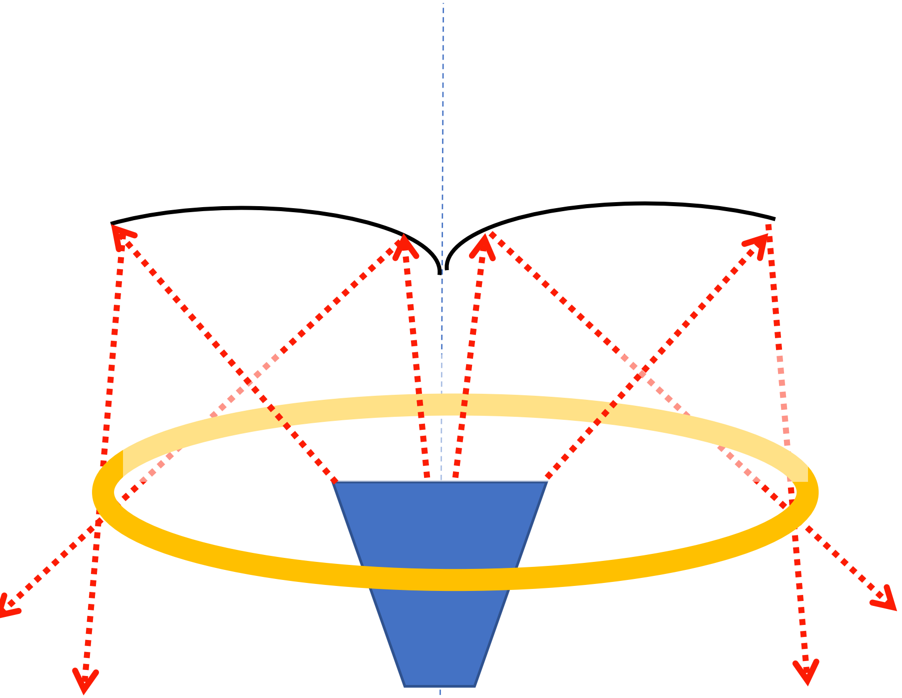




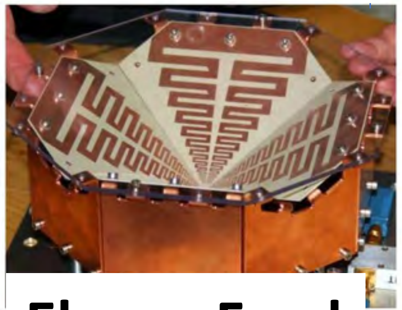


Broadband VLBI Development

独自で広帯域受信機を開発



～120deg.



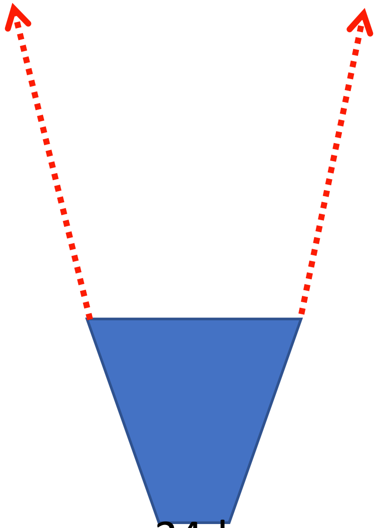
Eleven Feed

QRFH

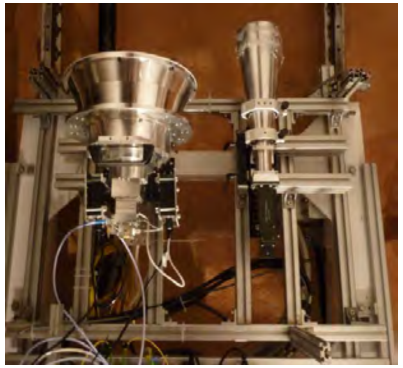
要求性能：

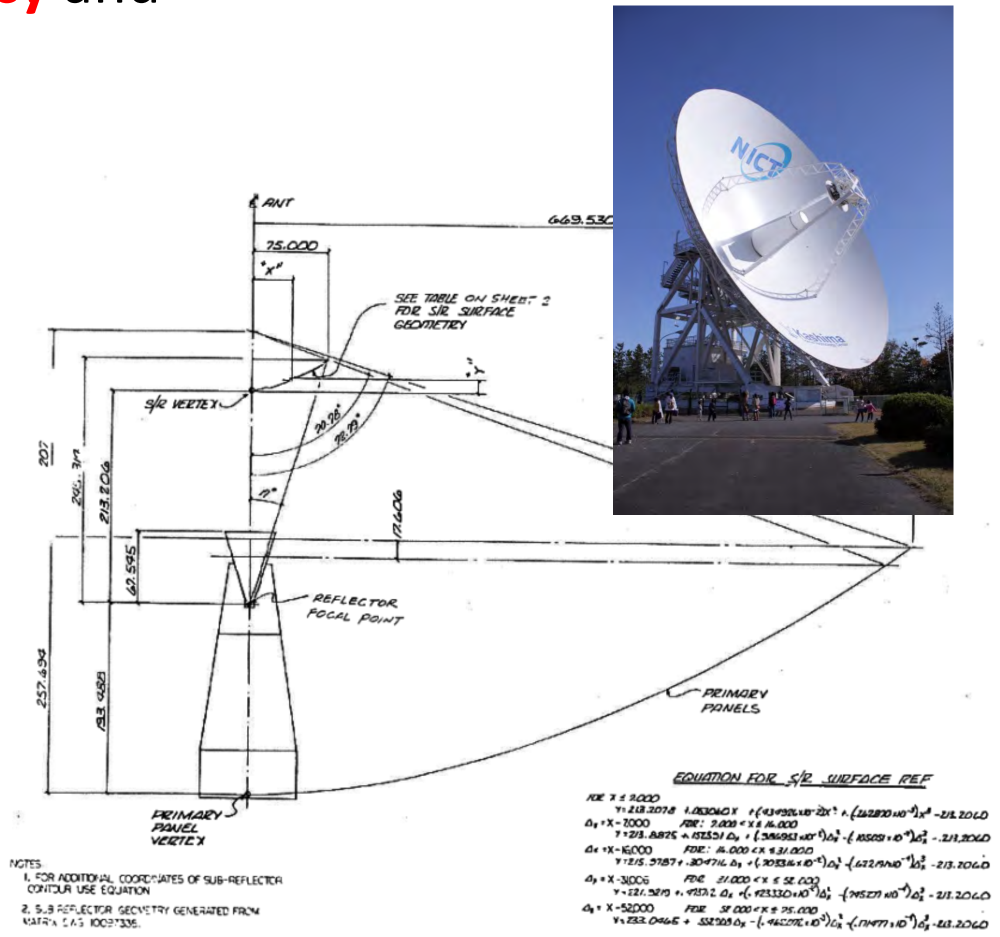
Broadband Frequency and

Narrow beam width



～34deg.





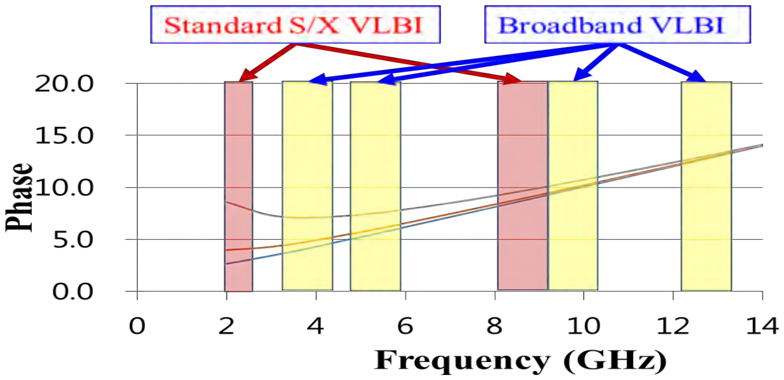
Broadband Feed and RF-Direct Sampling

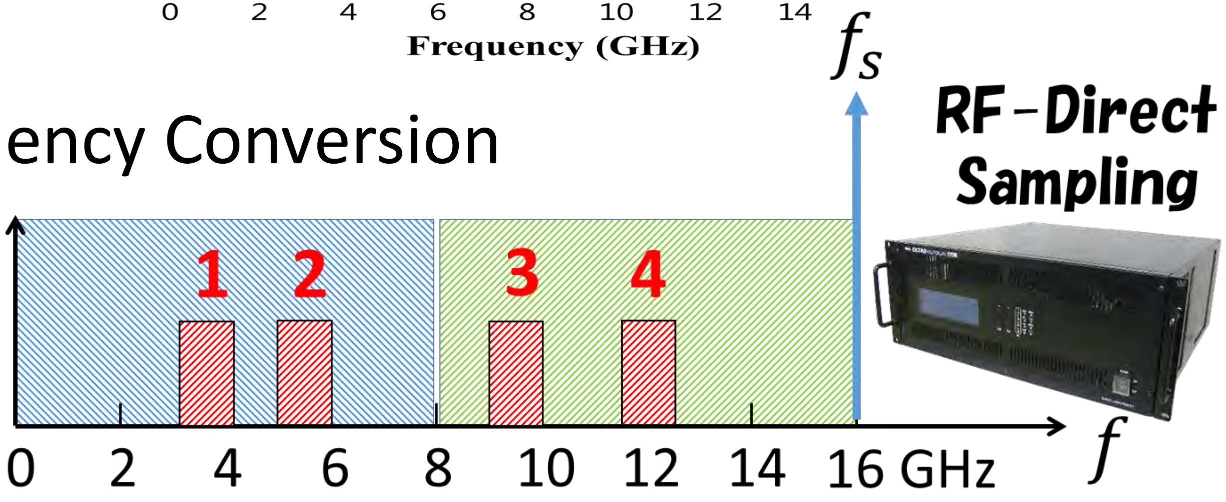
- Broadband VLBI, 3-14 GHz range

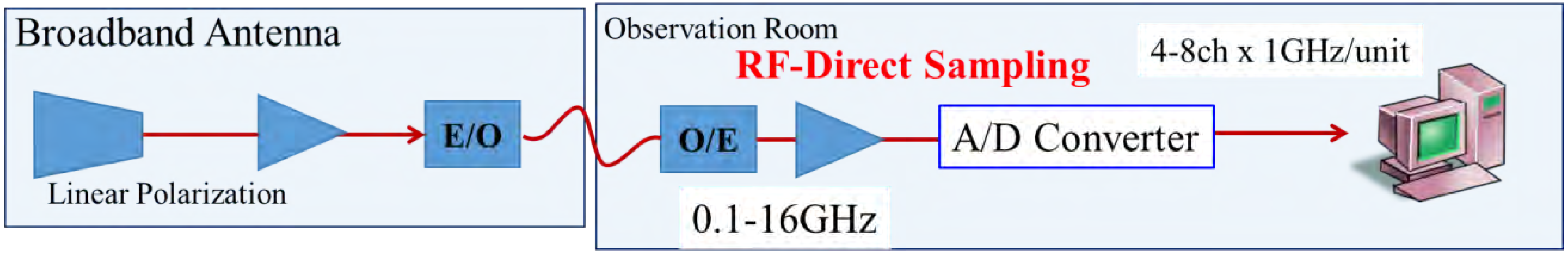
  One order large bandwidth

  → one order fine delay precision.

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







新しい遅延観測量の利用

Node-Hub Style (併合遅延を利用)

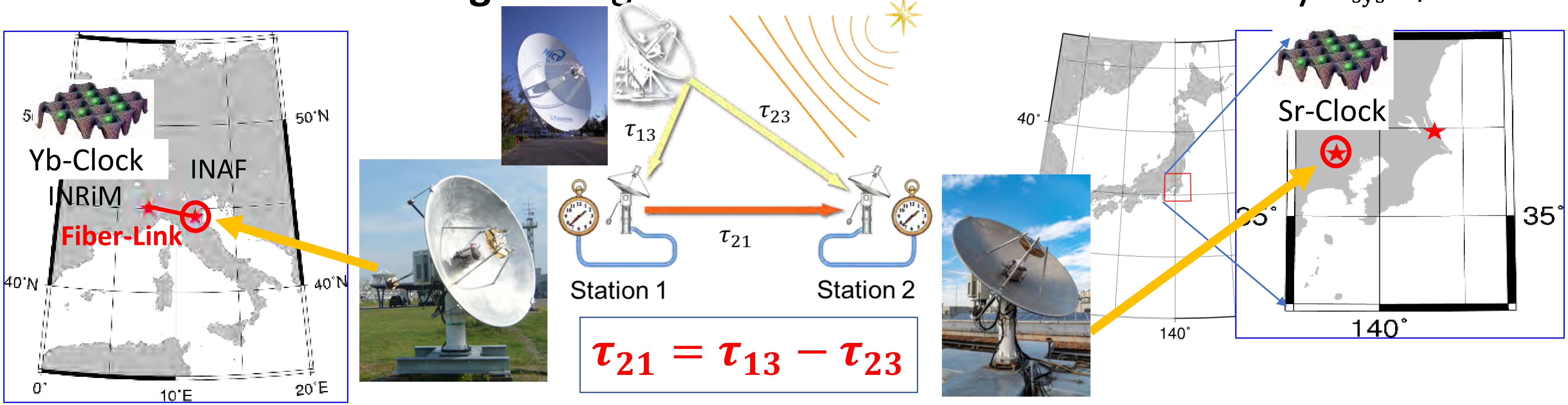
$$\tau_{21}^{NHS}(t_1) = \tau_{23}(t_1) - \tau_{13}(t_1) + \tau_{13}(t_1)\dot{\tau}_{21}(t_1)$$

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

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

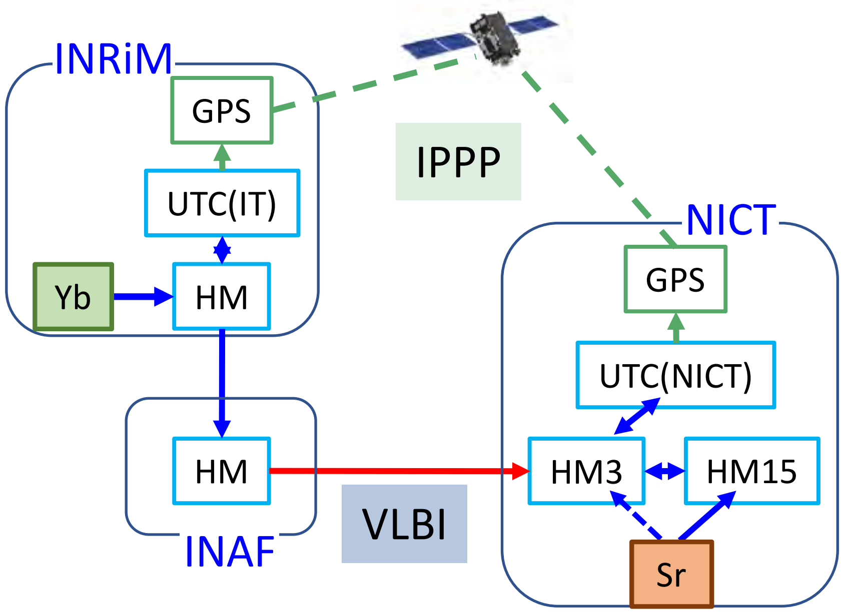
D_n : Diameter
S : Radio Flux
η_n : Efficiency
T_{sys}: System noise.

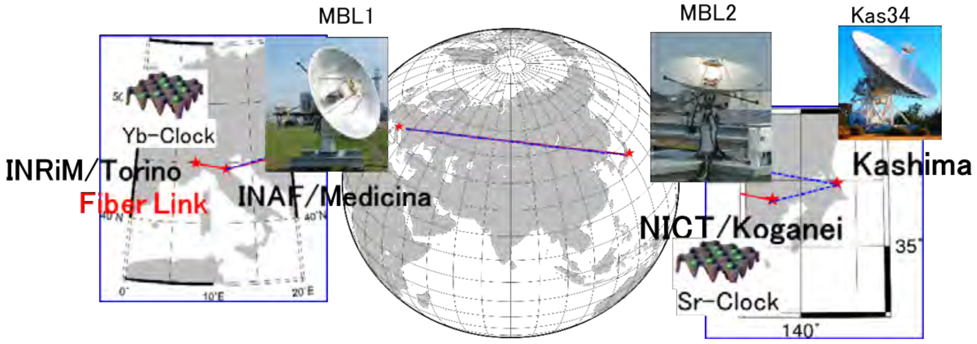
- **Cancel effect:** Large station(Grav. Deformation, Cable delay)
- **Easy deployment**(Small antenna): low-cost, transportable
- **Potential advantage:** mitigation of radio source structure delay

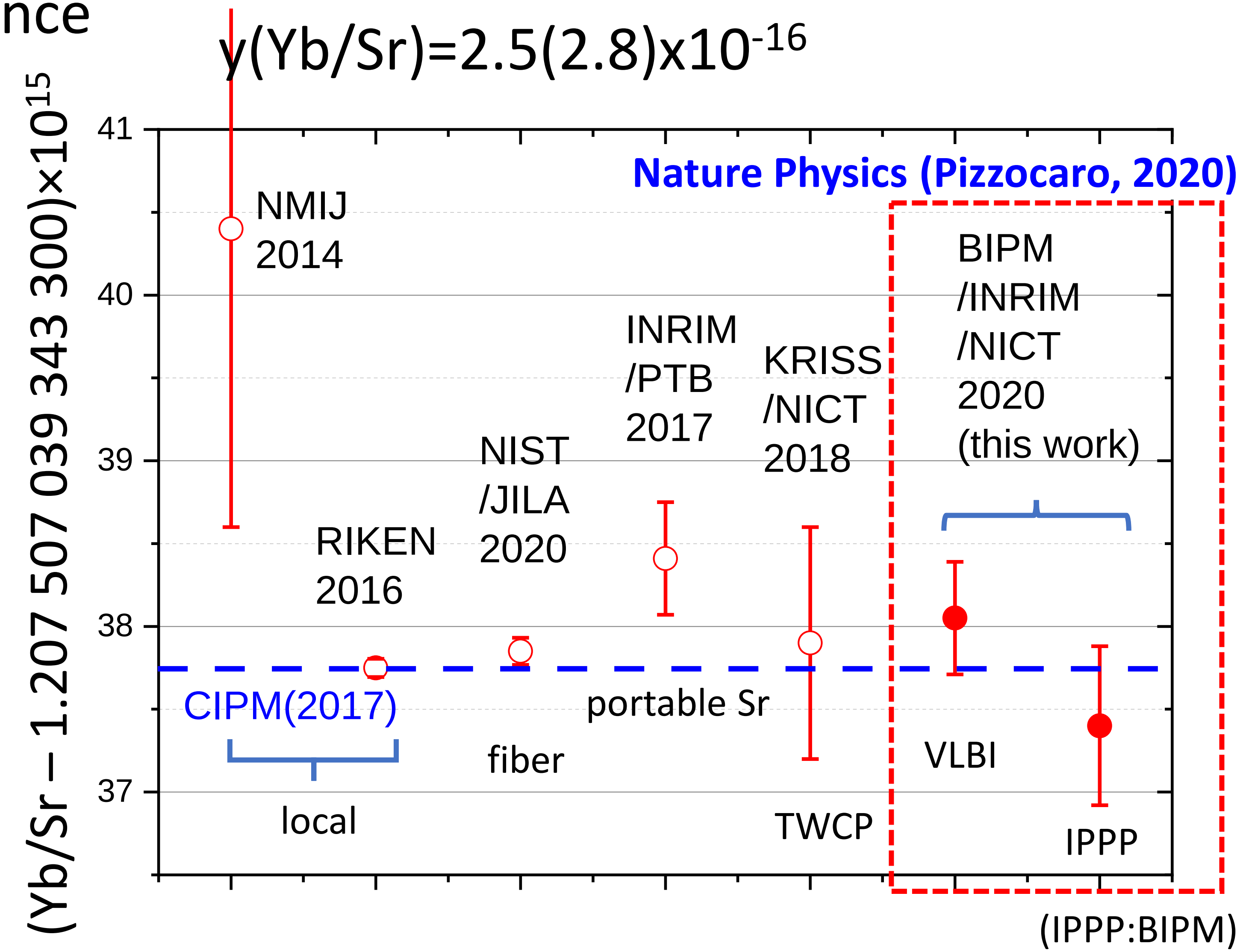


Yb/Sr 光格子時計間の周波数リンク

Best precision for 9000 km distance

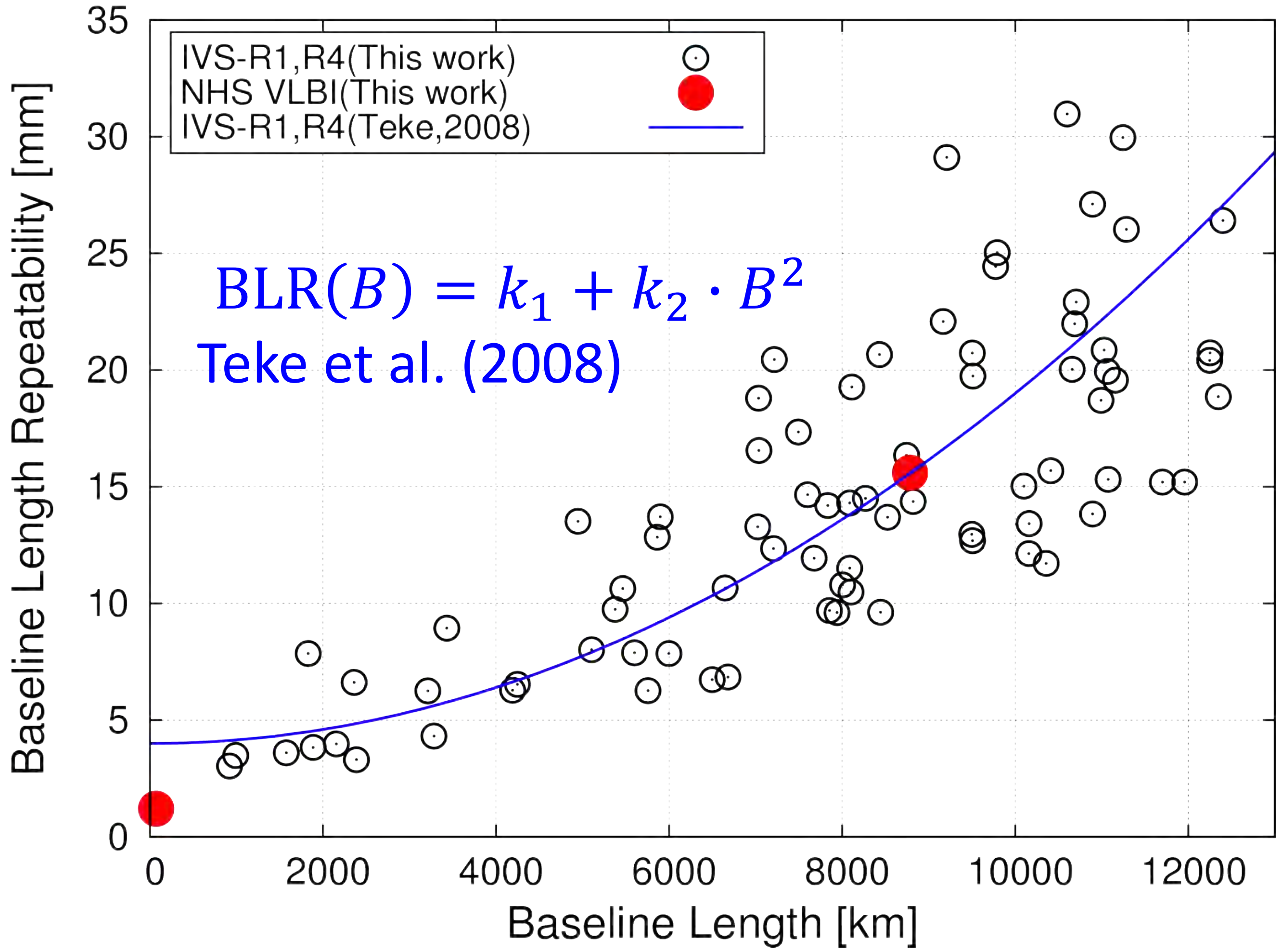


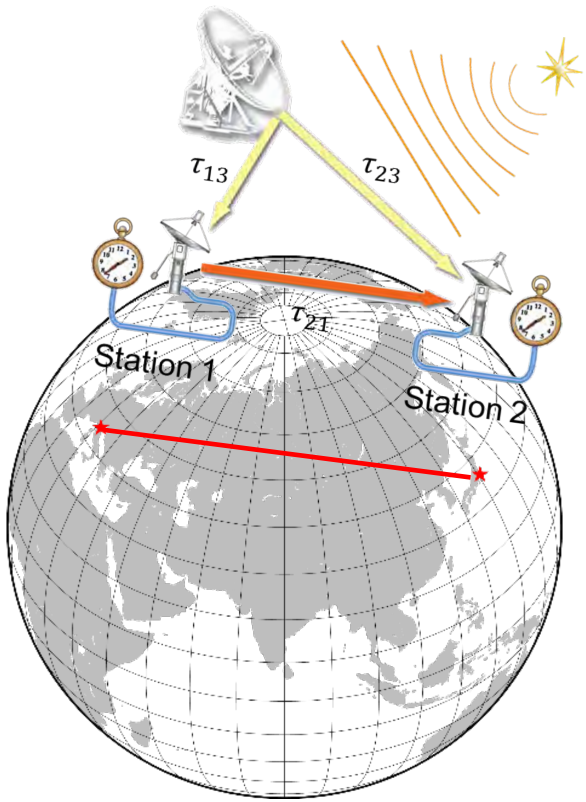




基線長再現性 (BLR)

2.4m-2.4mアンテナ間のNHS VLBI 観測は、IVS-R1,R4 セッションの観測と同等のBLRを実現した。





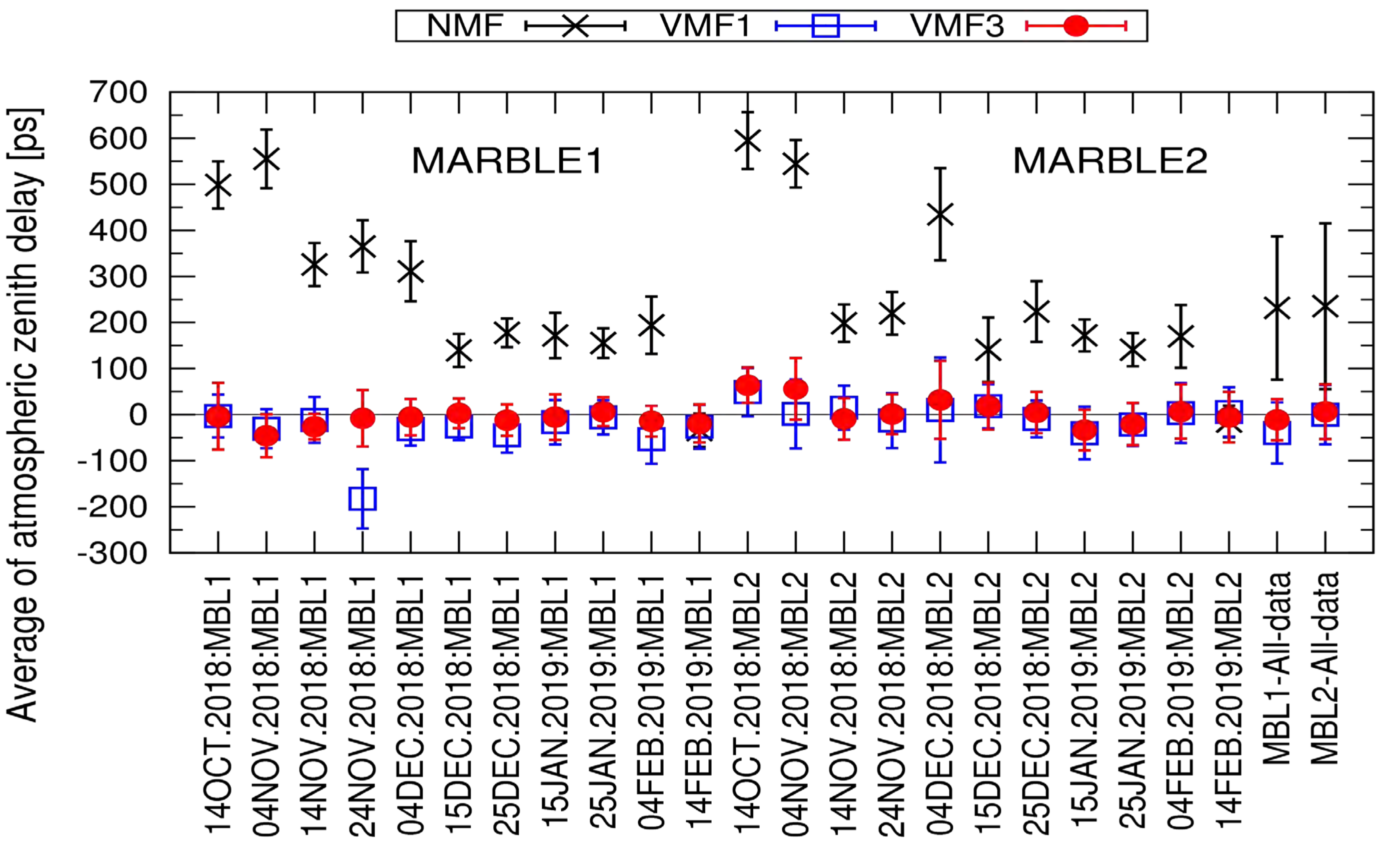
M.Sekido et al.(JoG, in printing)

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.

天頂大気遅延残差の平均 が小さい(<数10ps)
→ VMF3の精度の良さ.

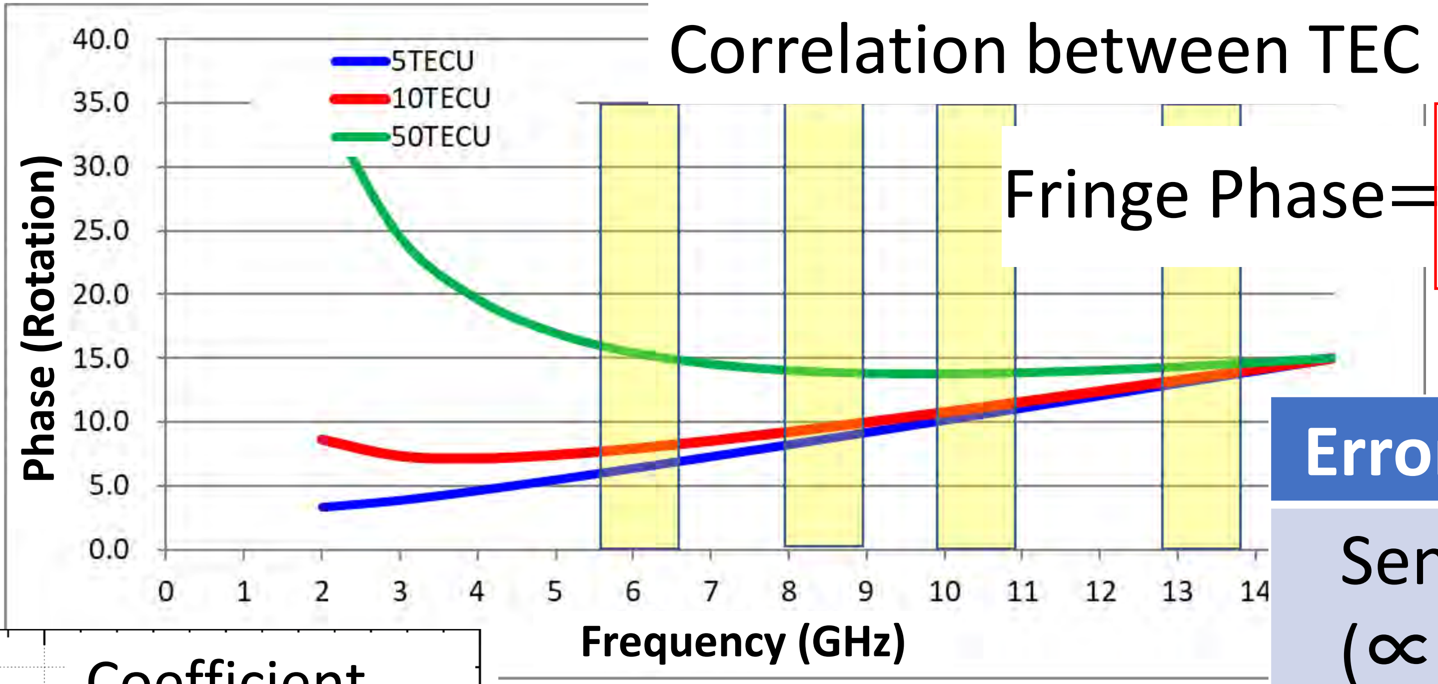


The VMF3 (Vienna Mapping Function)
Based on ECMWF(European Centre for Medium-Range Weather Forecasts) numerical weather model

- 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

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

Error Source	uncertainty
Sensitivity (∝1/SNR)	6.4 ps
Instrumental	12.7 ps
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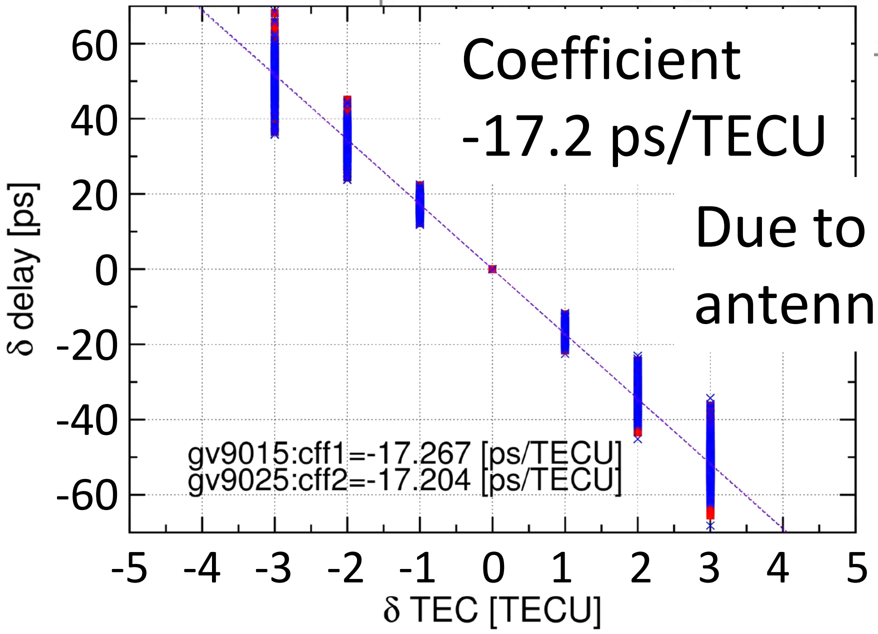
Radio Source Structure	22-33 ps



Coefficient
-17.2 ps/TECU

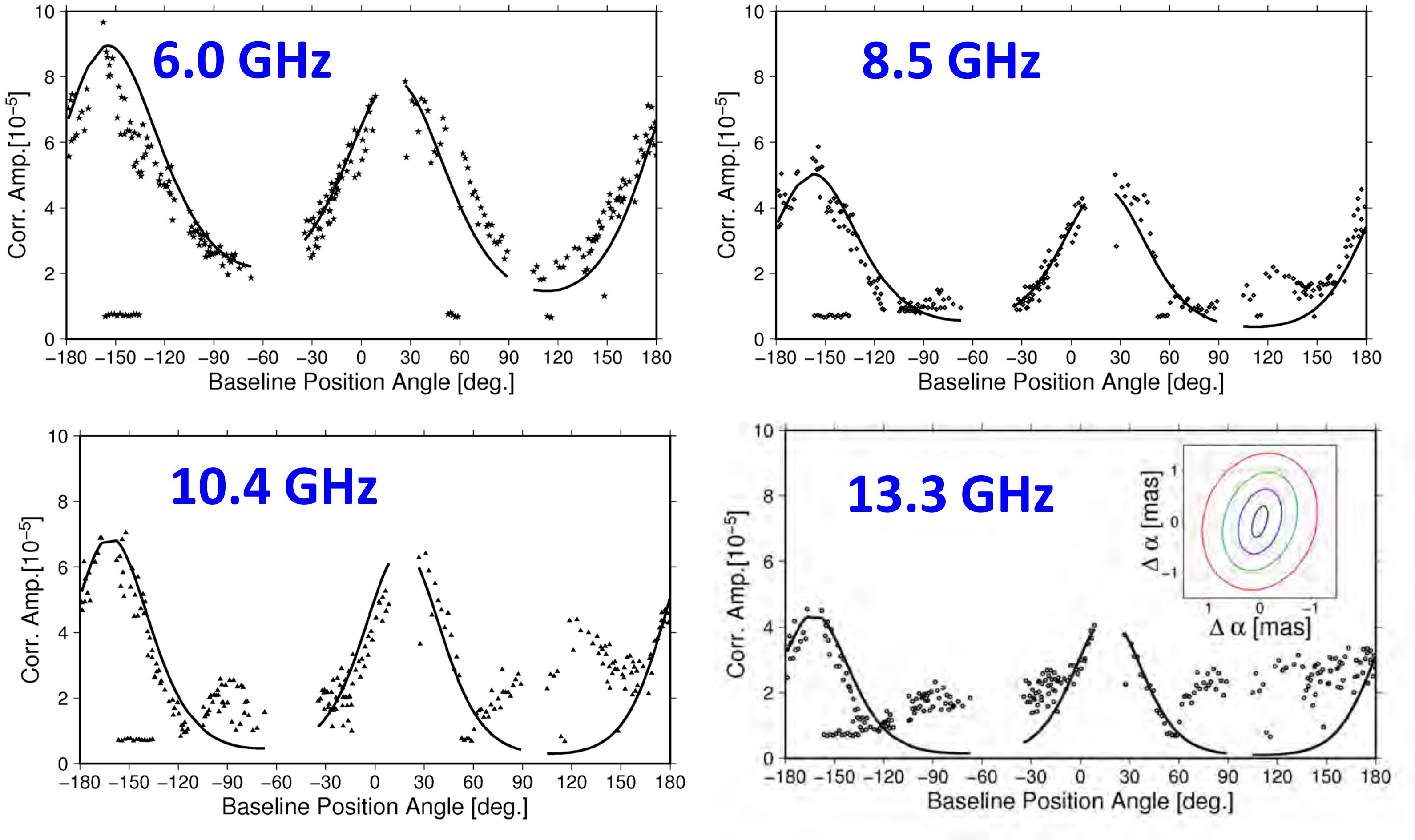
Due to limited SNR of small antenna, TEC error was 0.1-1 TECU.

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

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**.

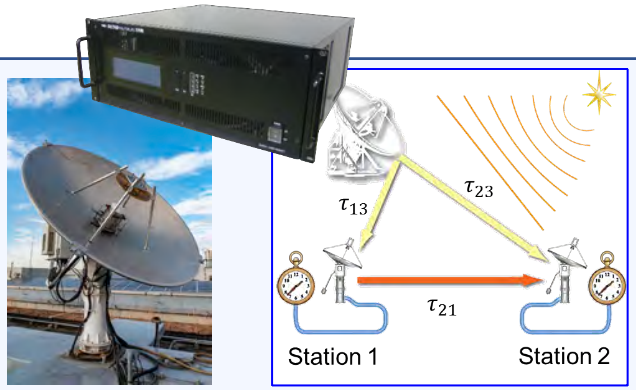
Radio Source:1928+738



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

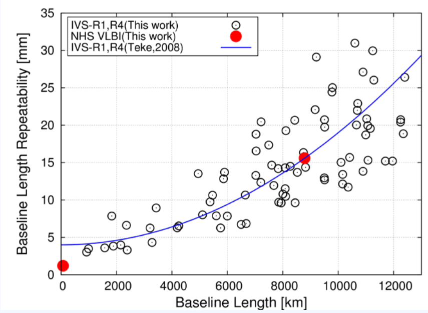
Summary

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.