Broadband geodetic VLBI system and its application to optical clock comparison

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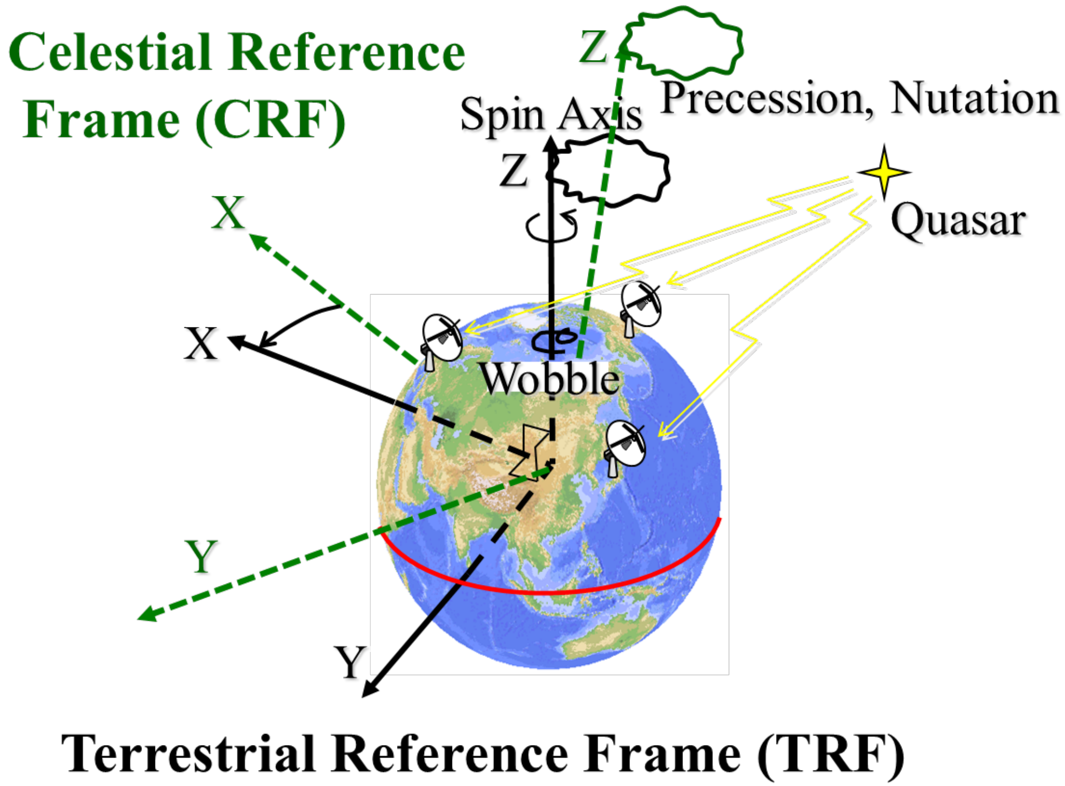
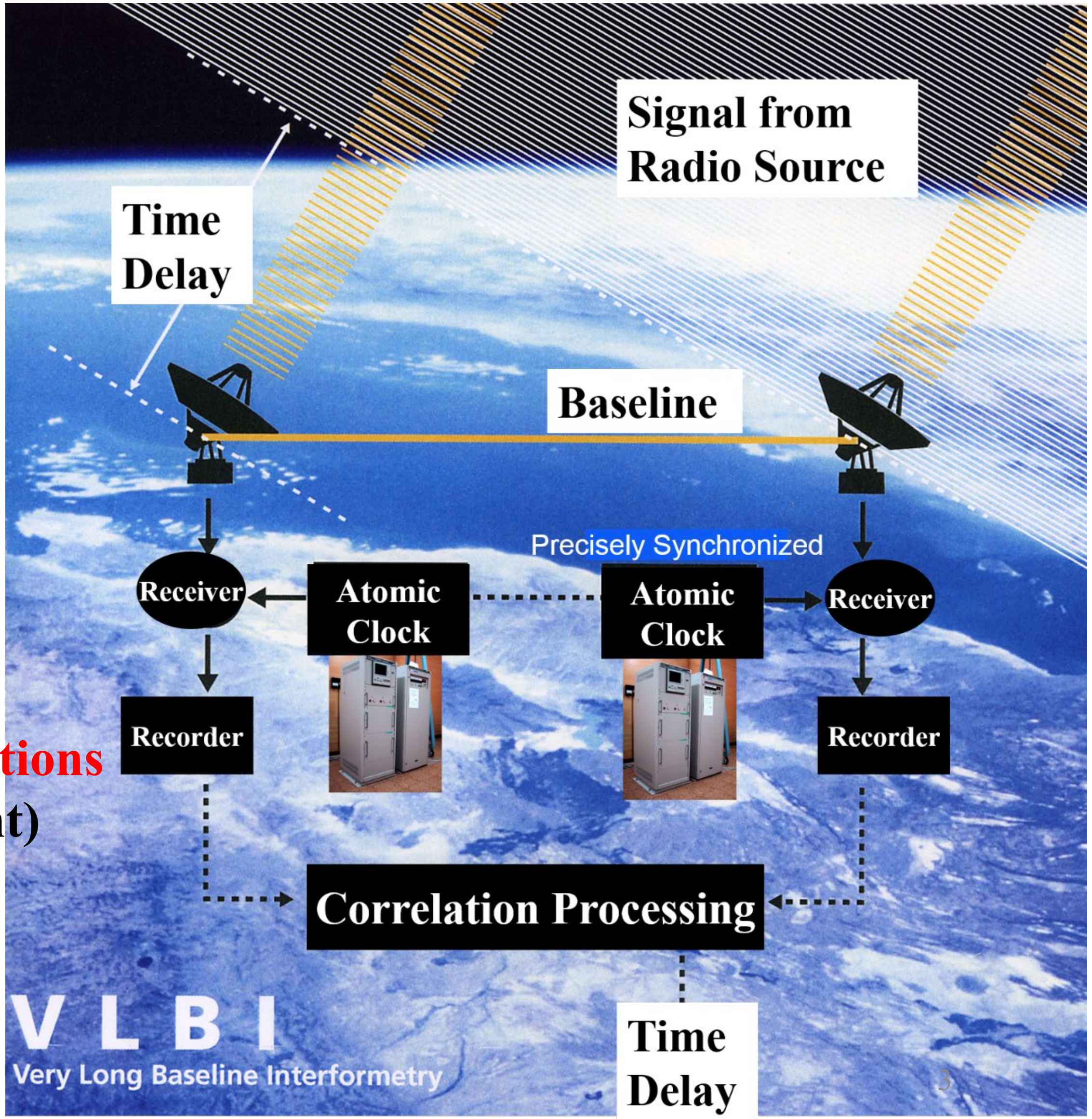
Introduction and Background

lattice-Clock

- Optical frequency standards with accuracy below 10^{-16} have been developed in metrology community.
- Current definition of 1 second by Cs microwave emission is going to be replaced by optical frequency emission from certain kind of atoms in near future.
- Precise frequency comparison between several kinds of candidate atoms/ions of optical frequency standards are required. Especially accurate frequency comparison over intercontinental distance is expected.
- Accuracy of $< 1\text{x}10^{-16}$ is a target.

What is VLBI : Measure of spatial coordinates





Measurement of frequency difference between distant locations

= Measurement of difference of gravitational potential **(geoid height)**

Gravitational time dilation

$$d\tau/_{dt} = 1 + \frac{U}{c^2} \ , \qquad U: Gravitational\ Potential$$

1.e-16 frequency diff. ~ 1m height

Why Freq. Transfer with VLBI?

Technique	By means of	Orbit info Dependency	Radio Signal Transmission	Accuracy	Running Cost
TWSTFT(*)	Communication Satellite	Slight	Need License	< 1.e-15 (Code) < 1.e-16 (Carrier Phase)	>10k USD/yr.
GNSS	GPS /GNSS satellite	High	--	< 1.e-15 (IPPP)	Low
VLBI	Celestial Radio Sources (CRF)	--	--	< 1.e-15 (Broadband)	Low (**)

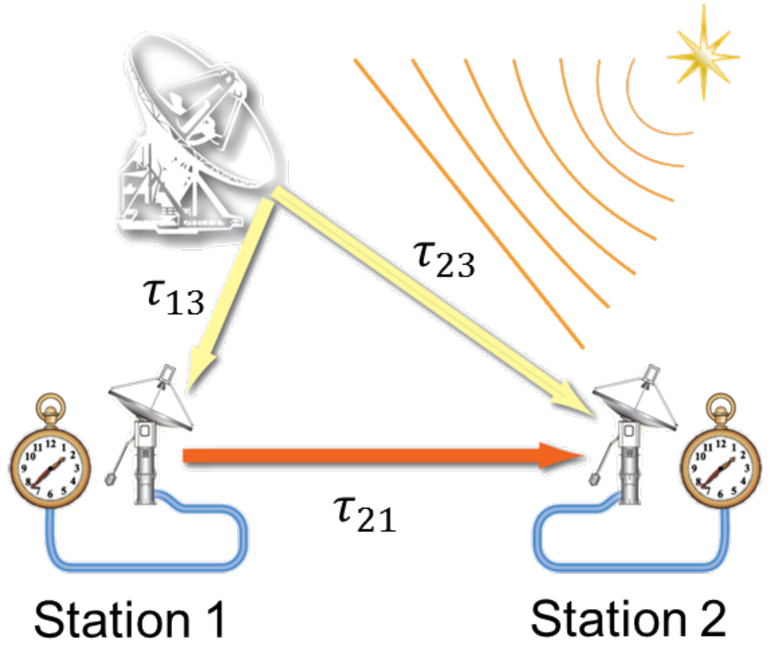
* Two Way Satellite Time and Frequency Transfer

** Running cost of small VLBI station is low, although large dimeter antenna may not be.

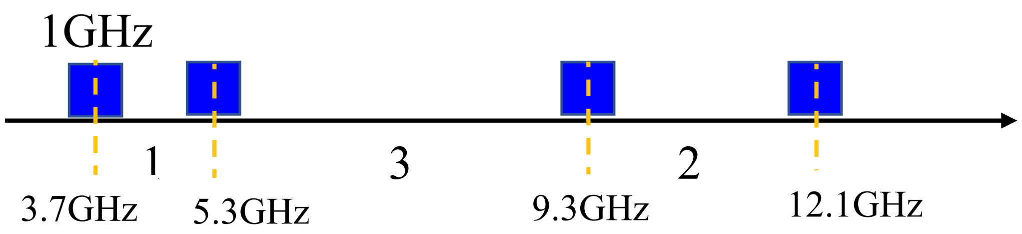
- (Stability)VLBI uses distant radio sources as fiducial point in the sky. Long time stability can be expected in VLBI Frequency link. Broadband group delay is free of ambiguity.
- (Passive measurement) does not require any radio transmission licensing and communication satellites, can be used anywhere and anytime.
- (Geoid Comparison)In addition to spatial coordinate (ICRF, ITRF, and EOP), VLBI will be able to contribute to geoid comparison.

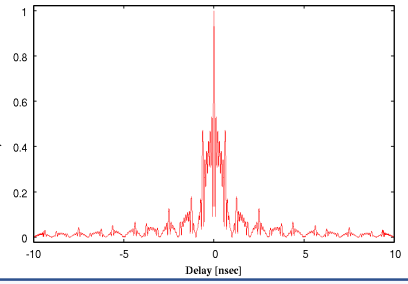
GALA-V Project Overview

Frequency comparison via transportable broadband telescopes.



- ■Radio Frequency： 3.2-14 GHz (mostly VGOS compatible)
- ■Data Acquisition： 4 band (1024MHz width/band)
  - ■ Nominal Freq. Array : Fc=3.7GHz, 5.3GHz, 9.3GHz, 12.1GHz
  - ■ Effective Bandwidth：3.3GHz (10 times wider than conventional system)



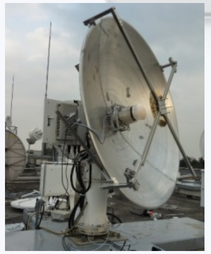


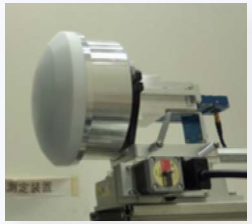
$$\tau_{21} = \tau_{13} - \tau_{23}$$

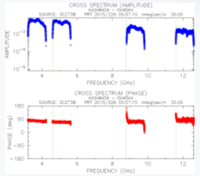
Closure delay is computed for small antenna pairs.

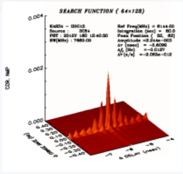
Broadband Feed for Cassegrain → RF-Direct Sampler → (VDIF Stream) Recording → Correlation GICO3 → Broadband Synthesis → Mk3DB → Calc/Solve

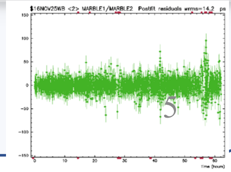
RF-Direct Sampler ↓ Compatible with Mk6, Flexbuf (jive5ab)









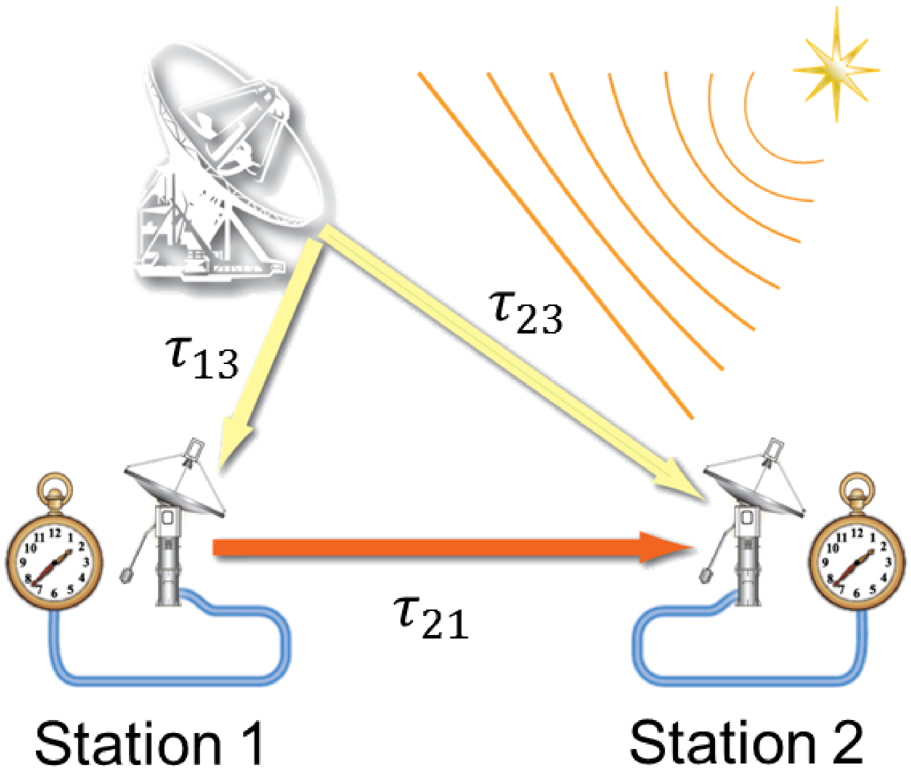


Broadband VLBI Experiments

'Node-Hub' style VLBI

- Closure delay relation used to derive delay between 'small-small' baseline.

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



- Advantages of using small antennas :
  - Quick slew and small distortion.
  - Large antenna's effects are canceled out.
  - Lower cost.
- Disadvantage:
  - Limited sensitivity, ←boosting SNR with large diameter telescope

    $$\text{Signal to Noise Ratio} \propto S\, D_1 D_2 \sqrt{\eta_1 \eta_2 / T_{sys1} T_{sys2}}$$

    D_n: Diameter, S:Radio Flux, T_{sys}:System noise
  - Source structure effects to closure delay.

Delay residuals of ‘Node-Hub’ style VLBI

34m-2.4m

OB

OD

2.4m-2.4m

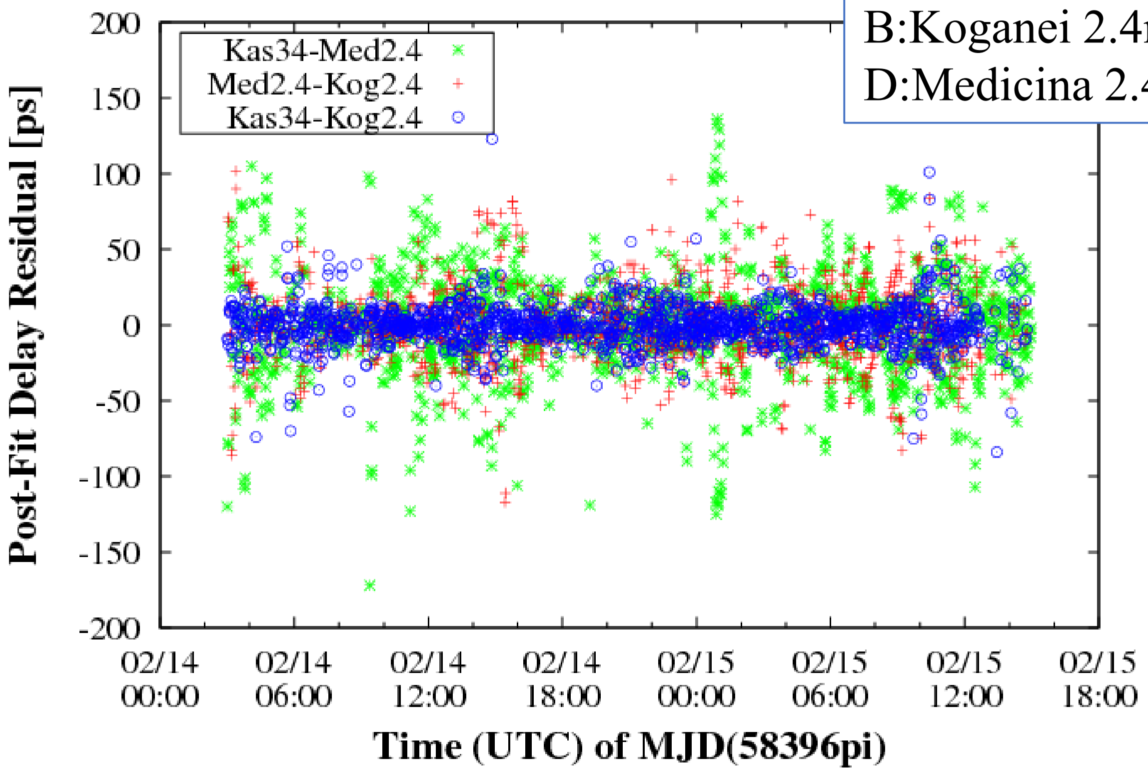
DB

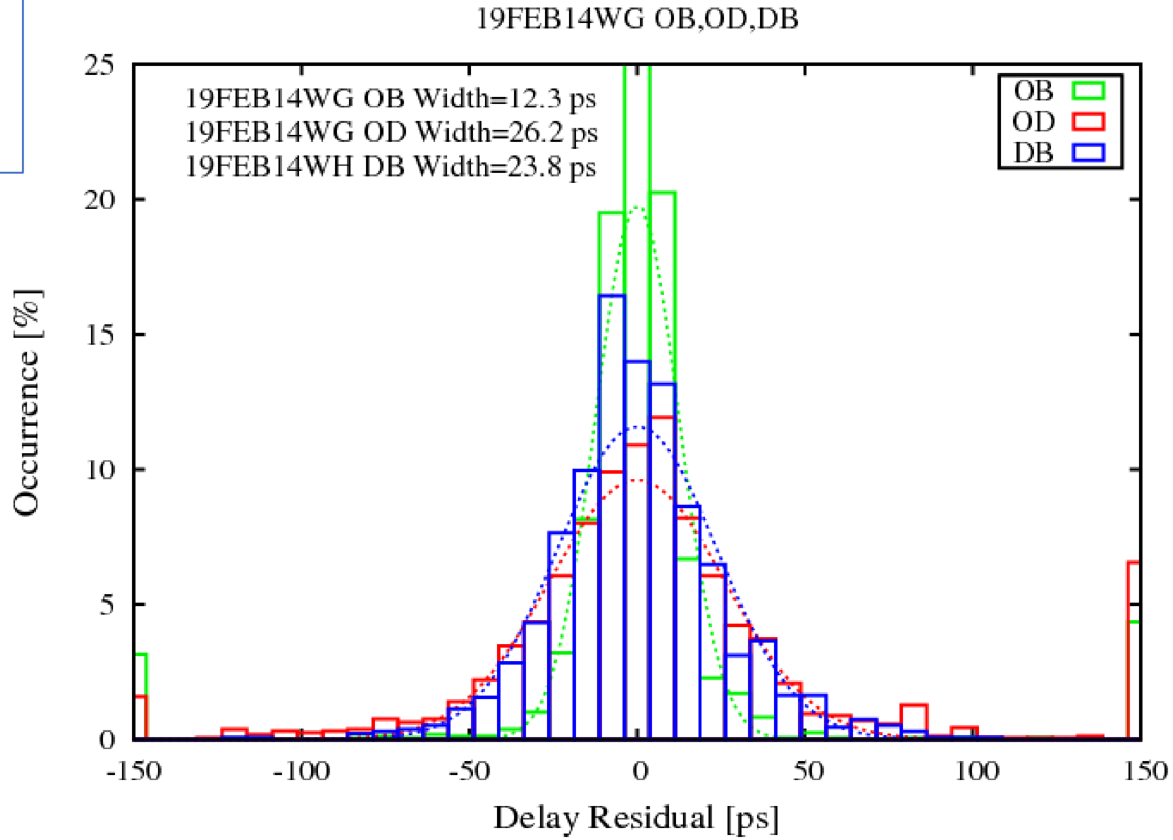
No degradation of delay residual after combination of NH-VLBI

- OB(100km) baseline residual ~ WRMS 12ps
- OD and DB (8700km) baseline ~ WRMS 26 ps, and 23 ps
- Baseline repeatability ~ 2cm

O: Kashima34m
B:Koganei 2.4m
D:Medicina 2.4m

19FEB14WG





Frequency Link Experiment : INRiM-INAF-NICT

Target: Intercontinental link of optical frequency standards

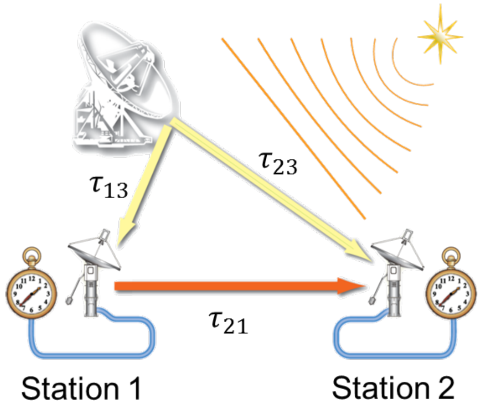
Opt-clock Operation: Sr by NICT Koganei, Yb by INRiM

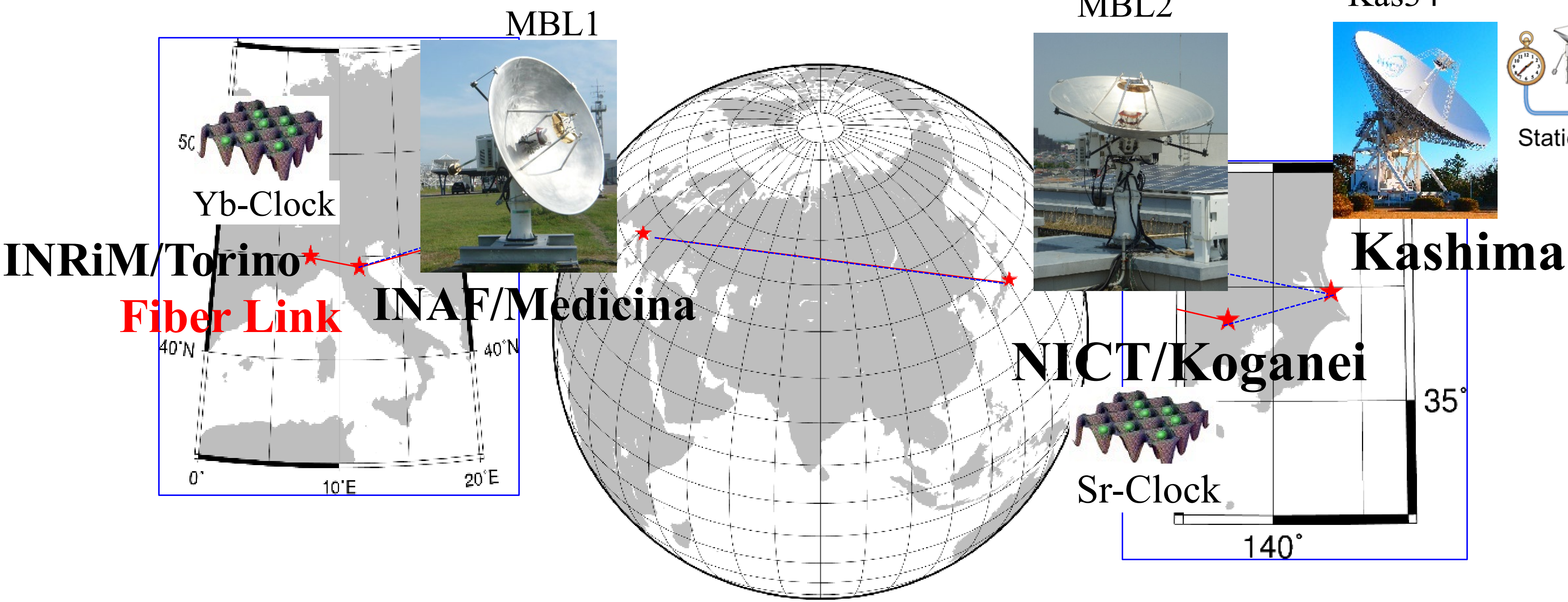
Experiments: 14 Oct. 2018 – 14 Feb 2019, 29-36 hours duration at 10 days interval..

Observation: Observing ICRF sources in the same way as for Geodetic VLBI.

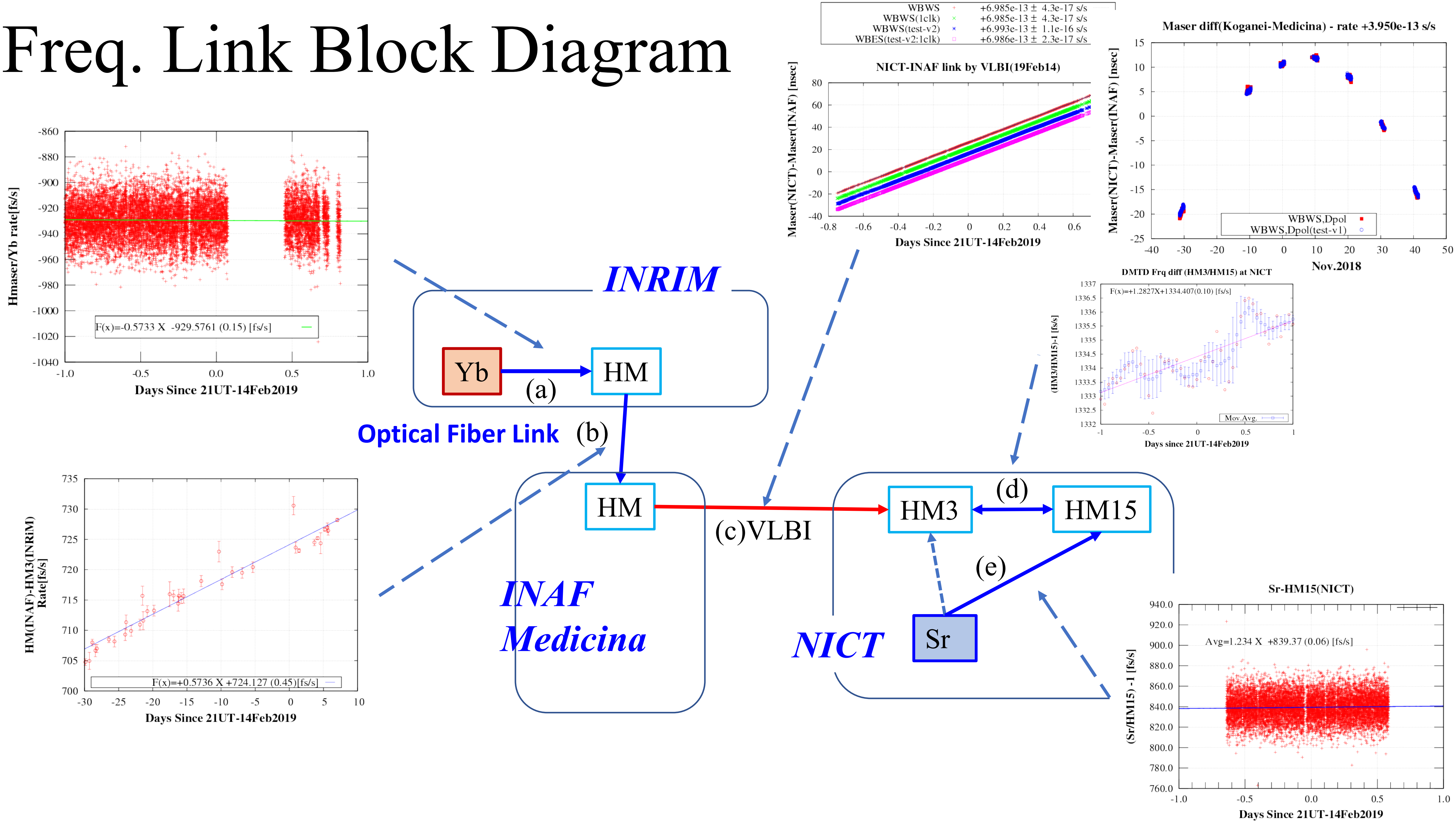
Frequency (6.0GHz, 8.0GHz, 10.4GHz, 13.8GHz)x 1GHz bandwidth.

Linear Polarization: Kashima34(V+H), MBL1(V), MBL2(V).



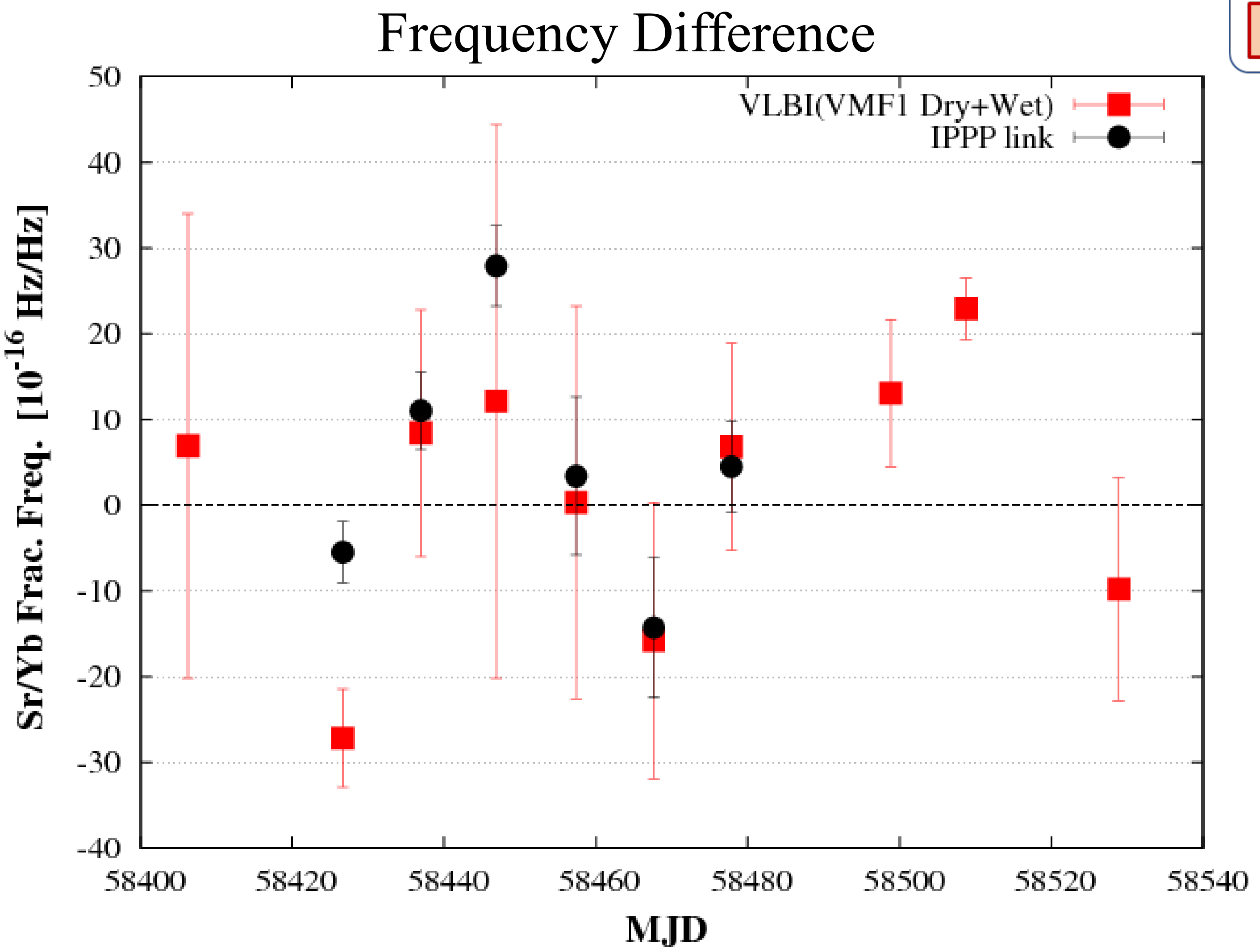


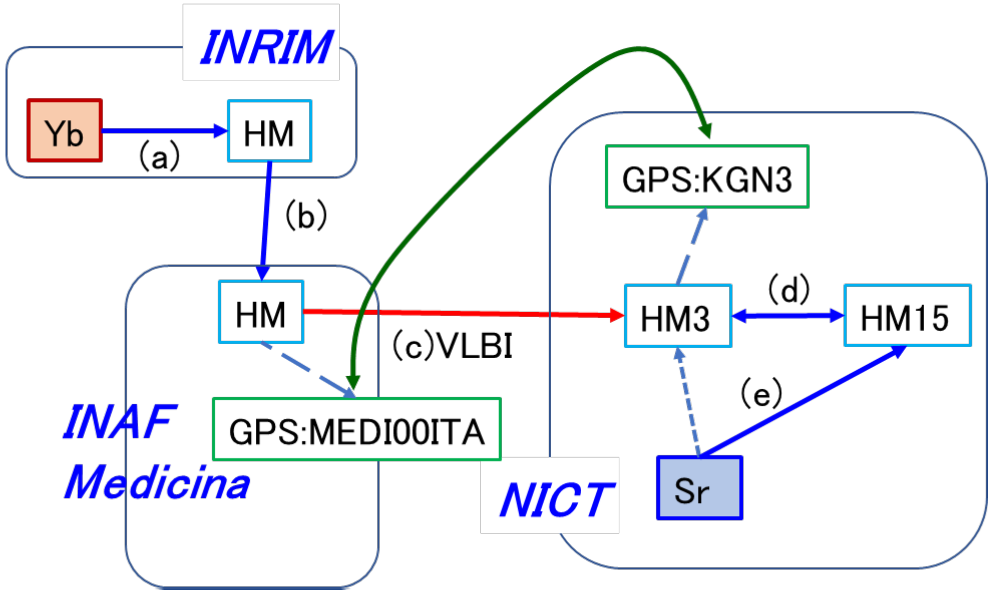
Freq. Link Block Diagram



Sr/Yb-link results. VLBI and GPS(IPPP)

Sr/Yb -1 : Fractional frequency difference is reported to be agree a part of 10^{-15}

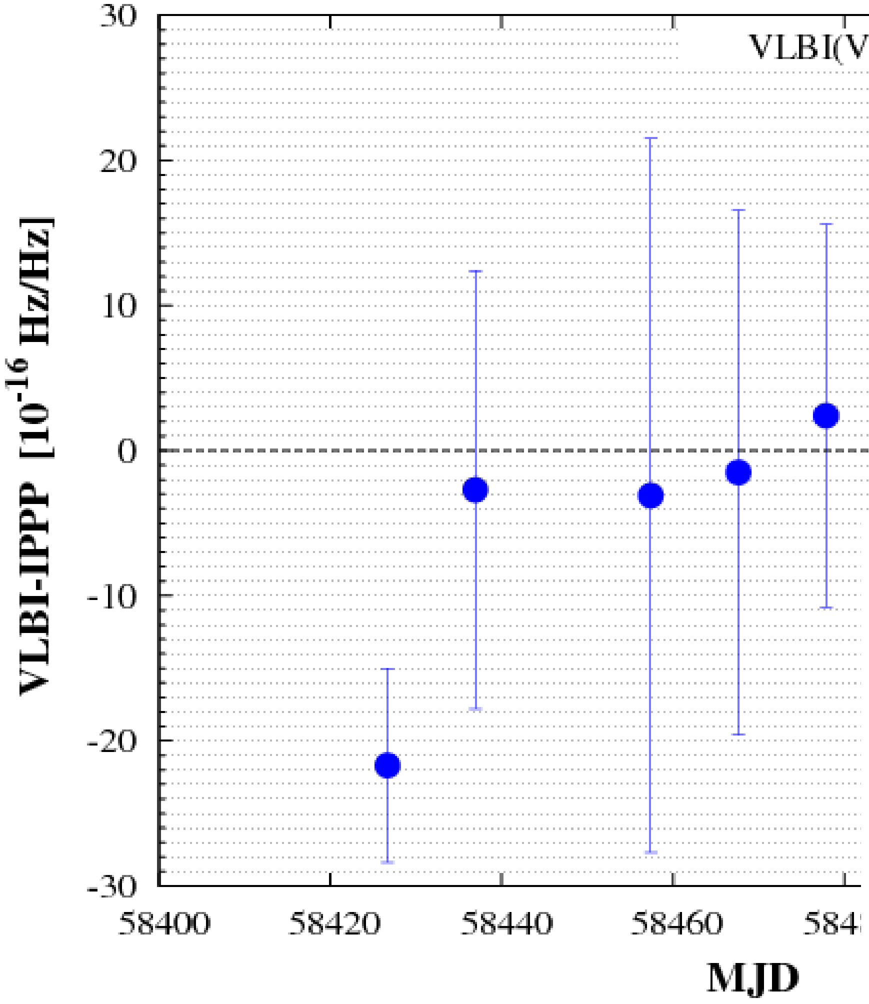


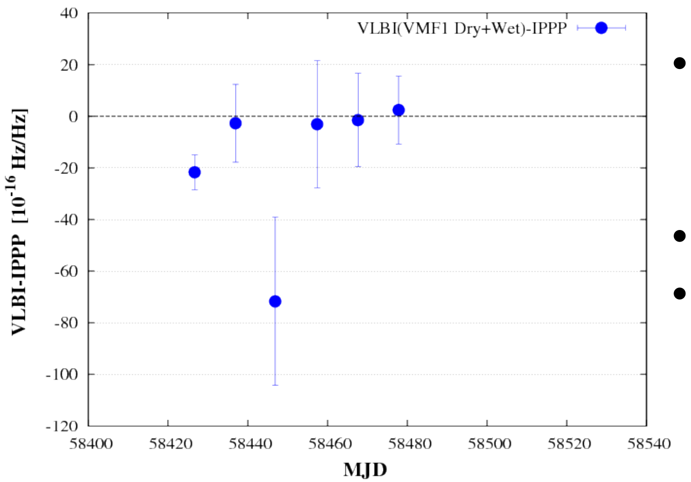


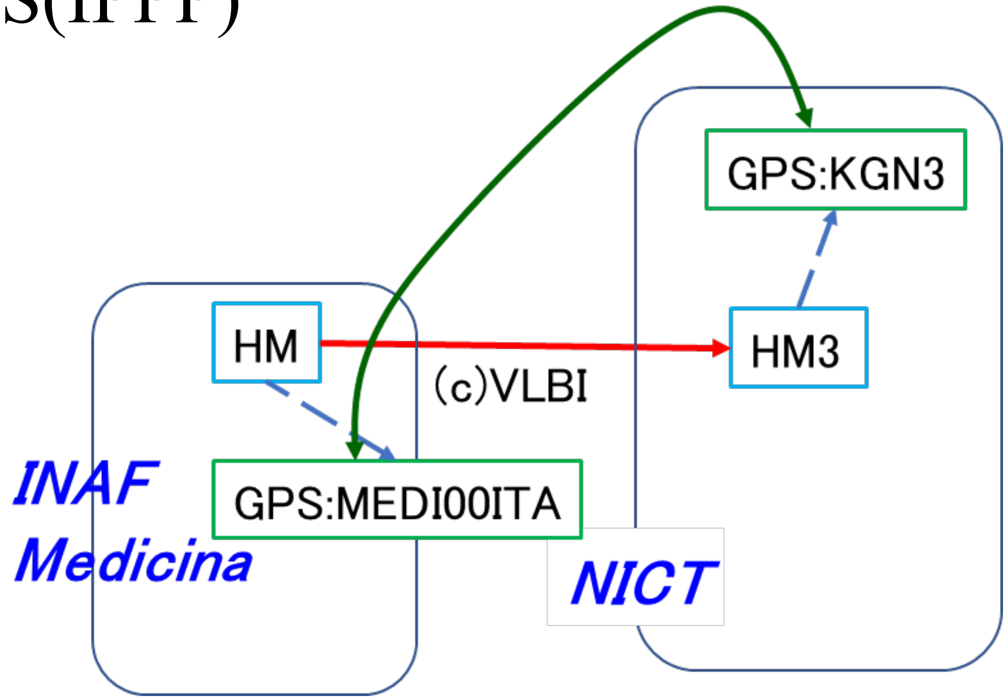
- GPS evaluation by the integer-ambiguous precise point positioning (IPPP) method provides a reference of comparison.
- IPPP is regarded as the best analysis for frequency transfer with GPS data. But GPS data at Medicina was not at perfect condition in this time.
- IPPP analysis is provided by curtesy of BIPM(J.Leute, G.Petit).

Evaluation of the VLBI-link with GPS(IPPP) as reference.

Double difference of Frequency link VLBI- GPS(IPPP)





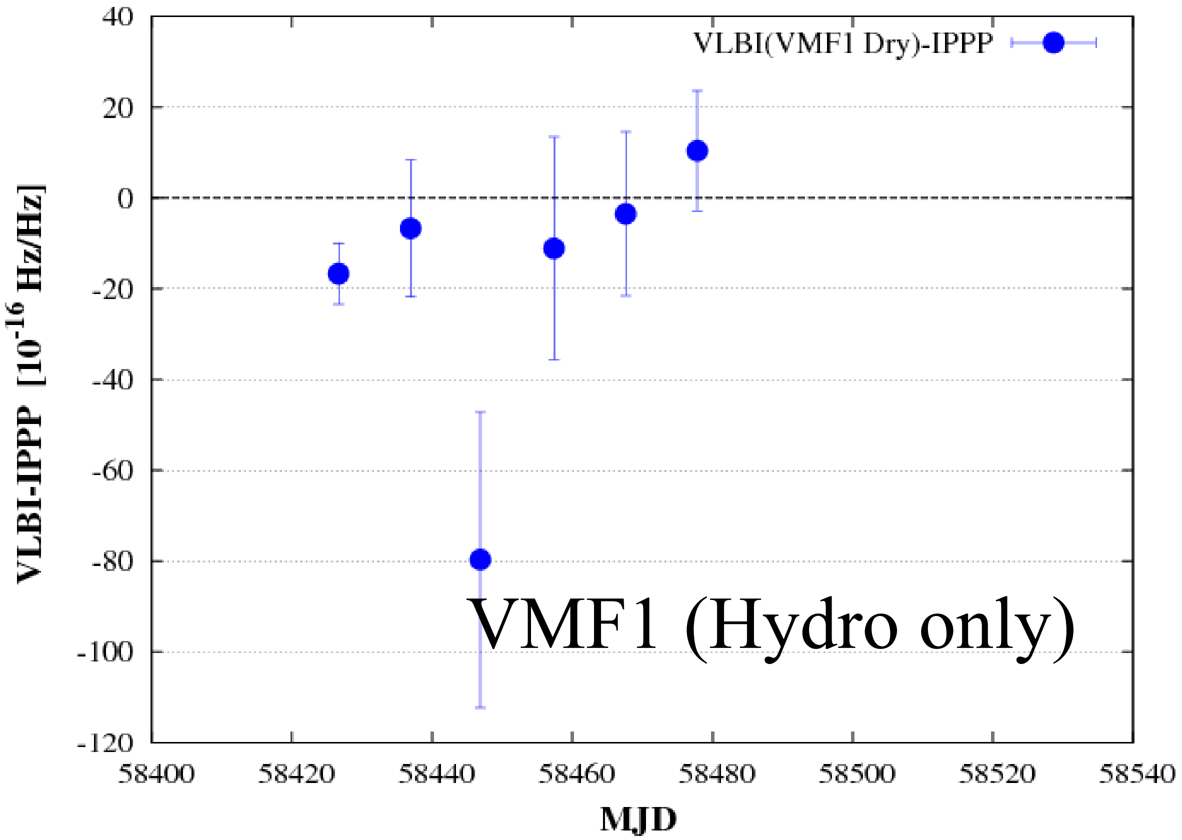


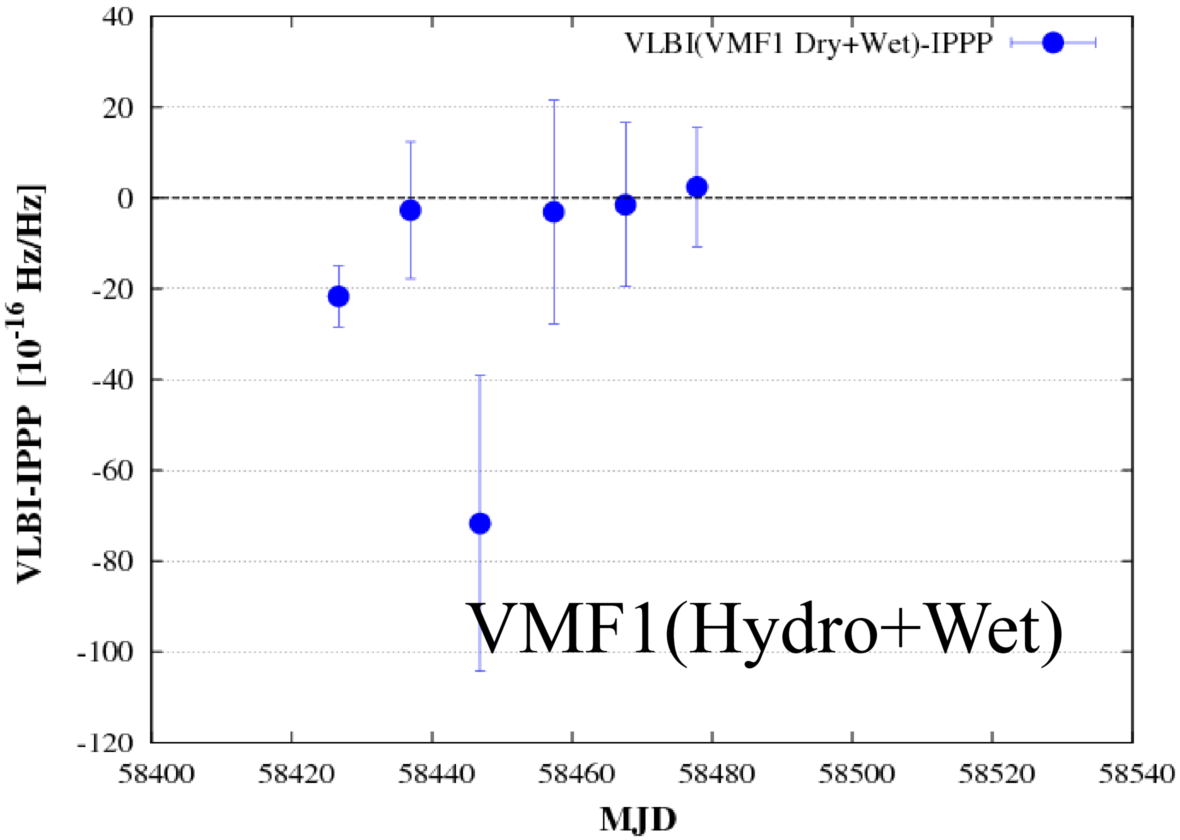
- VLBI-link seems to agree with IPPP solution (<4x10^{-16}) except for some sessions.
- GPS data condition was not perfect.
- IPPP solution was provided by curtesy of BIPM(J.Leute, and G. Petit)

Impact of Atmospheric delay calibration

Atmospheric delay calibration is important because of clock and atmospheric delay coupling.
We found the VLBI result approach to IPPP when using VMF1 (Vienna Mapping Function).
This is still a preliminary results, and further investigation is required.

VMF1: Journal of Geophysical Research Vol. 111, B02406, doi:10.1029/2005JB003629

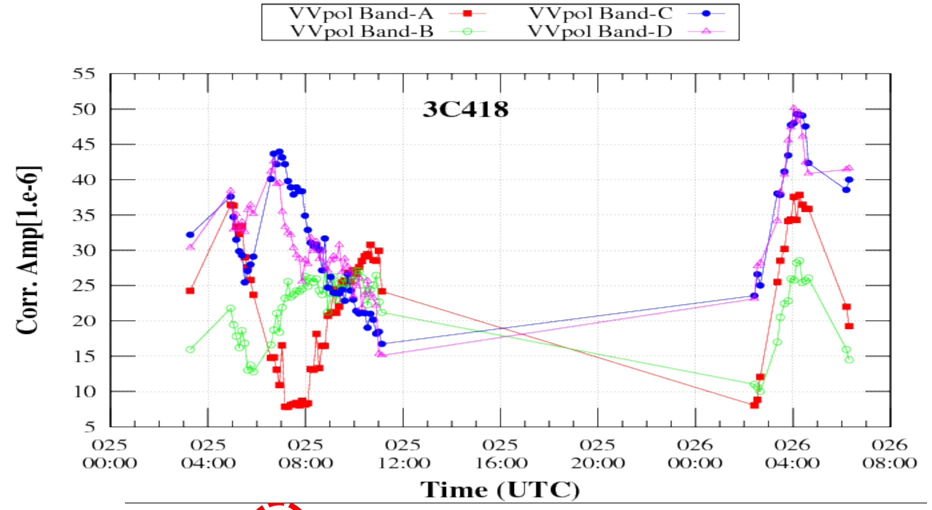


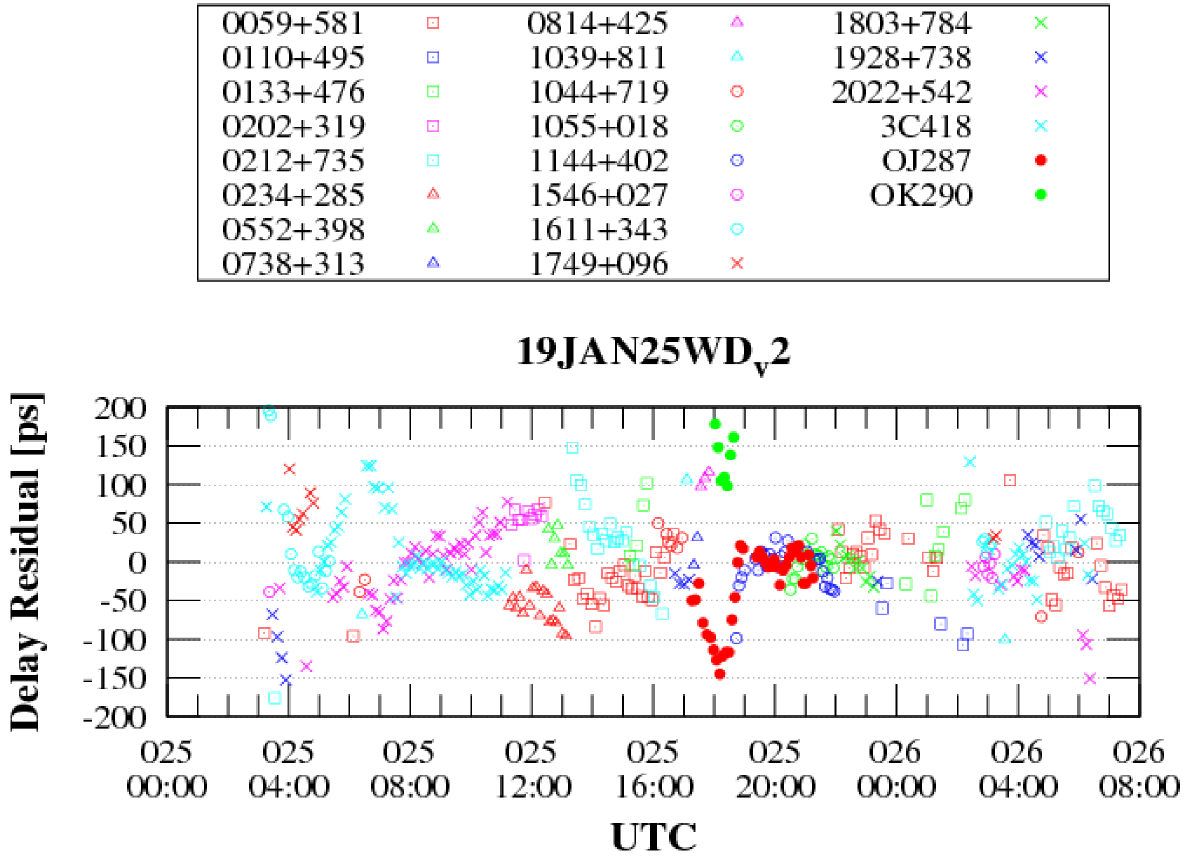


One of the Error Sources: Splitting Delay Residual of analysis

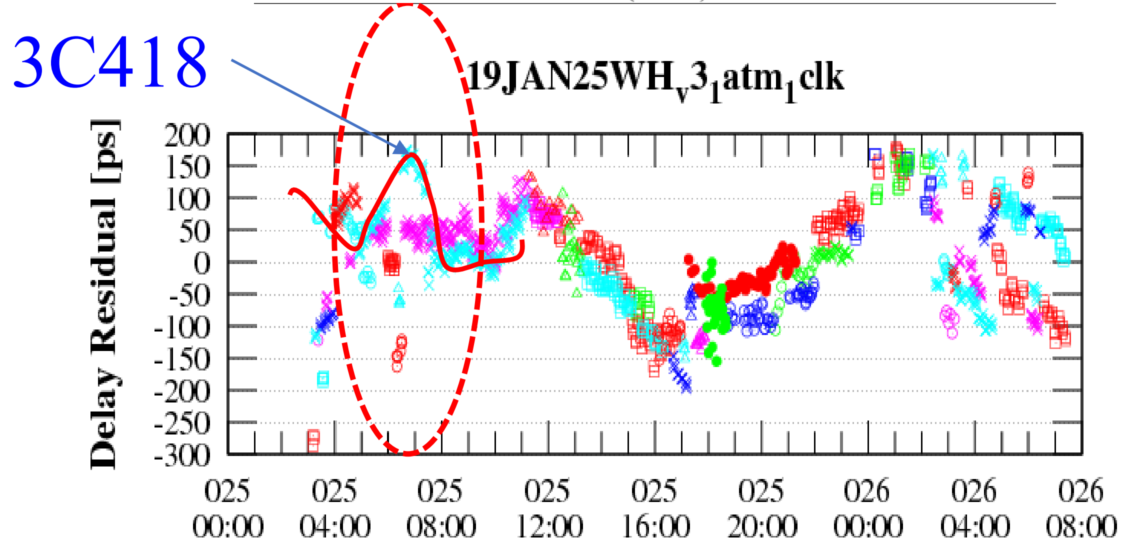
- VLBI group delay analysis O-C is delay residual.
- Our Delay residual shows source dependent systematic behavior.
- Similar deviation attribute to **radio source structure effect** is reported in VGOS network(S.Bolotin,2019;Ming Xu. ,2019)

Correlation Amp v.s. Time
by each 1GHz frequency band



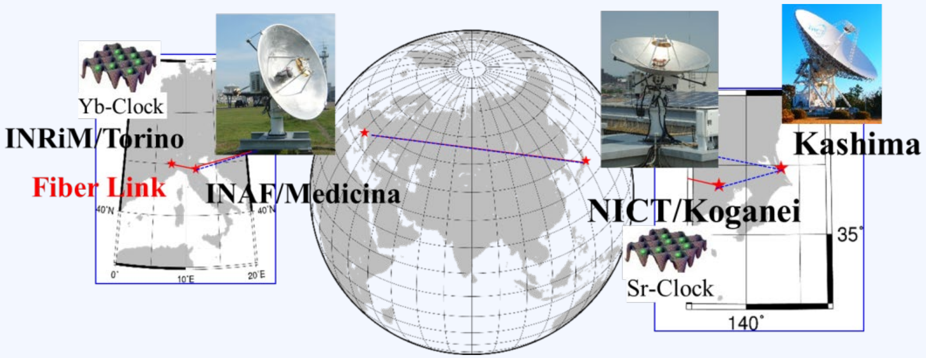


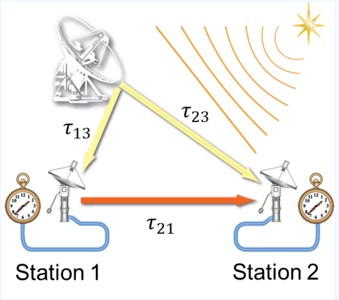
Delay residual with 1clock+Atm(20min.)+XYZ estimation.

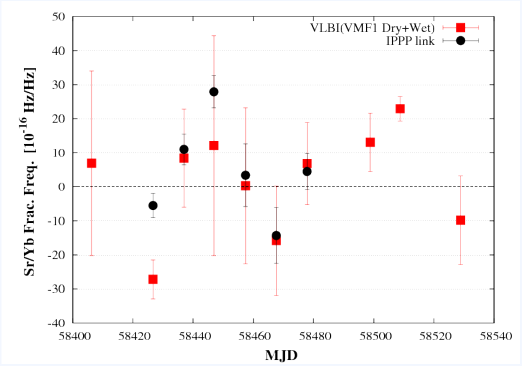


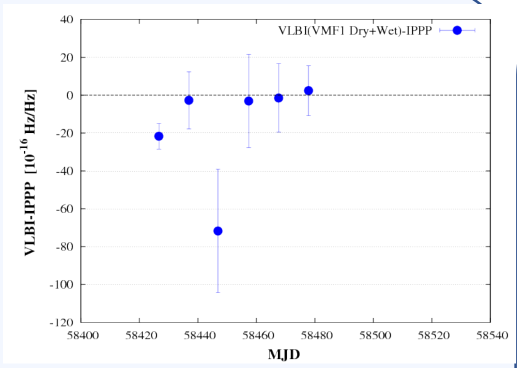
Delay residual with 1clock+XYZ estimation.

Summary









Optical frequency link with broadband VLBI between Italy-Japan is being conducted.

Sr/Yb frequency comparison is in progress.

1. **Broadband VLBI** system and transportable 2.4 VLBI station have been developed.
2. **Node-Hub style Broadband VLBI scheme** in our experiments works well with small(2.4m) Broadband VLBI station. This might be a future option of VLBI observation with low cost terminal.
3. We started **optical clock frequency link** experiments between **INRiM/INAF(Italy) – NICT(Japan)**. The results likely to be consistent with GPS(IPPP) as preliminary result.
4. Error sources and calibration technique need to be investigated: **Radio source structure** effect and **atmospheric delay calibration**.

Thank you for your Attention

Acknowledgements

- IPPP results were computed by J. Leute and G. Petit of BIPM using the CNES GINS software.
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- VLBI observation is supported by analysis software Calc/Solve, antenna control software Field System9, and scheduling software Sked, all developed by NASA/GSFC.