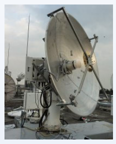
Intercontinental Comparison of Lattice Clocks using a Broadband VLBI Technique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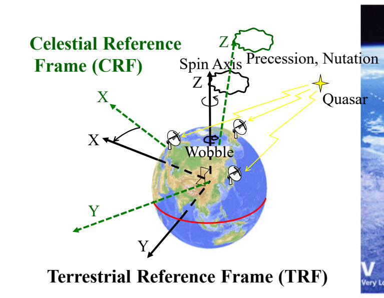
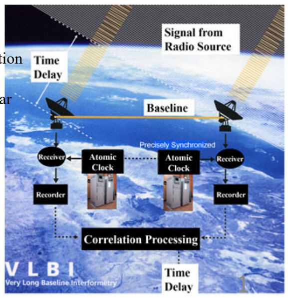
What is VLBI? Measurement of spatial coordinates





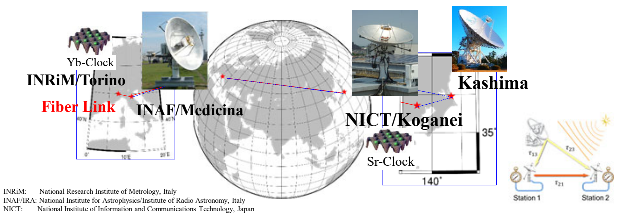
Technique	By means of	Orbit info Dependency	Radio Signal Transmission	Accuracy	Running Cost
TWSTFT	Communication Satellite	Slightly	Need License	< 1.e-15 (Code) < 1.e-16 (Carrier Phase)	>10k USD/yr.
GNSS	GPS /GNSS satellite	Highly	Free	< 1.e-16 (IPPP)	Low
VLBI	Celestial Radio Sources (CRF)	Free	Free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

- ❑ VLBI is one of space geodetic techniques maintaining spatial reference frames (ICRF, ITRF, and EOP). Time scale can be constructed consistently with these special reference frames.
- ❑ VLBI can be operated without using communication satellites. Japan-Europe time link is suffered from lack of communication satellites these years.
- ❑ VLBI uses fiducial radio sources in the sky. That leads to long time stability of VLBI measurements.
- ❑ VLBI does not need radio transmission license, thus can be used any time anywhere on the earth.

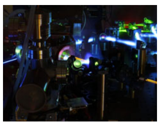
❑ Higher implementation cost (large antennas) is a disadvantage.
This could be overcome by using small diameter transportable stations with Broadband VLBI.

Intercontinental frequency link Experiment: INRiM-INAF-NICT using VLBI

Target: Intercontinental Frequency Link of Optical Frequency Standard. In addition to existing techniques: TWSTFT, GPS(PPP, IPPP)
Aug. 2018 :2.4m Antenna exported to INAF/Medicina, Italy



Other components: Two lattice clocks & a fiber link

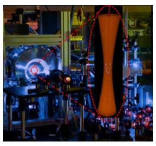


INRIM-Yb1
[Pizzocaro et al., Metrologia 54, 102 (2017)]
^{171}Yb optical lattice clock
CIPM: 518 295 836 590 863.60(26) Hz

Systematic effect:	Correction (10^{-16})	Uncert. (10^{-16})
Lattice light shift	-0.84	0.19
2nd order Zeeman	0.67	0.06
Clock laser light	<0.01	<0.01
BBR shift	23.68	0.14
DC Stark shift	0.2	0.2
Density	0.57	0.06
Background gas	0.05	0.02
Line pulling	0.0	0.1
Servo error	0.0	0.1
Total	**23.72**	**0.35**
Grav. red shift	-259.97	0.06
SRS		5.00

INRIM-INAF fiber link
[Clivati et al., Scientific Reports 7, 40992 (2017)]

Coherent fiber link
Telecom wavelength 1542 nm
Length 550 km
Connects the hydrogen masers at INRIM and INAF with uncertainty < 0.1×10^{-16}



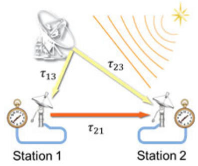
NICT-Sr1
[Hachisu et al., Opt. Express 25, 8511 (2017)]
^{87}Sr optical lattice clock
CIPM: 429 228 004 229 873.00(17) Hz

Systematic effect:	Correction (10^{-16})	Uncert. (10^{-16})
Lattice light shift	-0.02	0.38
2nd order Zeeman	5.13	0.03
Clock laser light	0.01	0.01
BBR shift	50.85	0.30
DC Stark shift	0.01	0.02
Density	0.13	0.15
Background gas	0.00	0.18
Line pulling	0.00	0.01
Servo error	0.53	0.15
Total	**56.63**	**0.56**
Grav. red shift	-83.41	0.22
SRS		4.00

GALA-V Project Overview

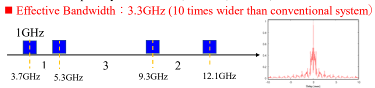
Frequency comparison by using transportable broadband telescopes.

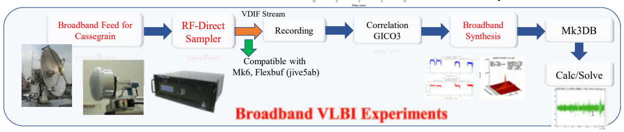
- ■Radio Frequency： 3.2-14 GHz
- ■Data Acquisition： 4 band (1024MHz width/band)
  - ■ Nominal Freq. Array : Fc=3.7GHz, 5.3GHz, 9.3GHz, 12.1GHz
  - ■ Effective Bandwidth：3.3GHz (10 times wider than conventional system)



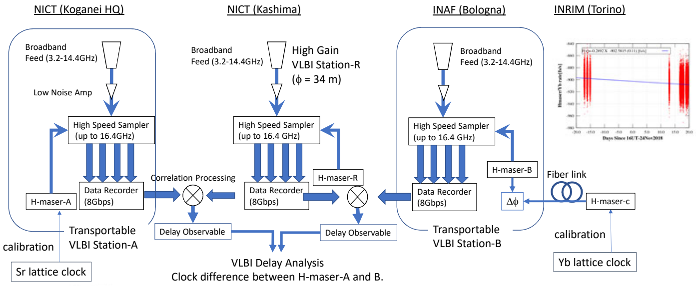
$\tau_{21} = \tau_{13} - \tau_{23}$

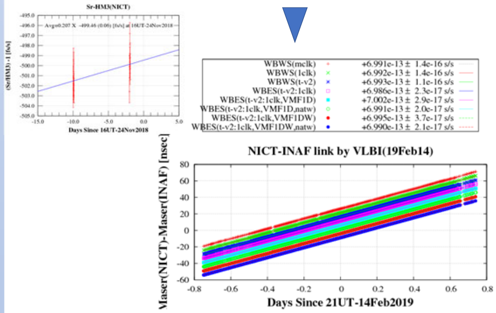
Closure delay is computed for small antenna pairs.





Link scheme





Sr & Yb lattice clock

Intermittent operations several times per months

VLBI measurement

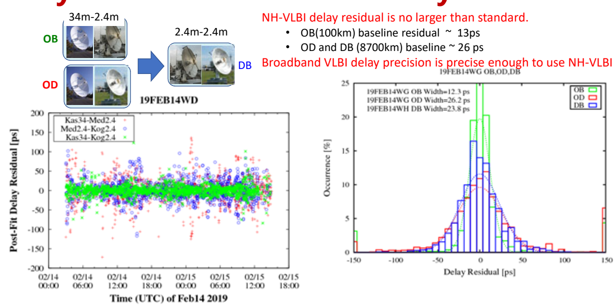
- Correlation analysis indicates the delay between two HMs
- Intermediate Kashima 34m antenna improves S/N
- 36 hours observation, once per 10 days due to the capacity of disk and data transmission
- Bandwidth and polarization synthesis in four bands to improve S/N.

Delay residuals of ‘Node-Hub’ style VLBI

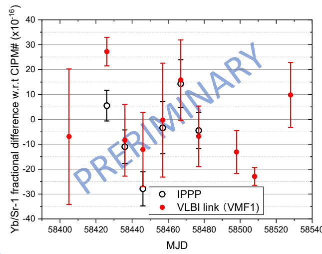
NH-VLBI delay residual is no larger than standard.

- OB(100km) baseline residual ~ 13ps
- OD and DB (8700km) baseline ~ 26 ps

Broadband VLBI delay precision is precise enough to use NH-VLBI



Result



- Atmospheric delay is the dominant uncertainty in VLBI link
- Various map functions (NMF, VMF1Dry, VMF1Dry+Wet) attempted.
- Tentatively, the difference among the map functions is regarded as the uncertainty of VLBI link here.
- Dead time link-uncertainty not included.
- Evaluations of uncertainty in frequency link required.
- IPPP uncertainty is 5×10^{-16} in 28 hours.

Total weighted means of VLBI points and IPPP link agree with zero within the standard error of points

IPPP solution is a courtesy of J. Leute and G. Petit.

Acknowledgements

IPPP results were computed by J. Leute and G. Petit of BIPM using the CNES GINS software.

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High speed data transfer(~5Gbps) of VLBI data is enabled by JIVE5ab developed by H.Verkouter.

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