NICT VLBI Analysis Center Report for 2019-2020

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Abstract VLBI Analysis activity of NICT is targeting for development and application of broadband VLBI for precise frequency comparison. Pair of small diameters broadband VLBI stations are used for the nodes of the frequency comparison, and high sensitivity antenna support the VLBI observation by boosting the sensitivity (‘Node-Hub’ Style: NHS). This NHS VLBI observation scheme was used for frequency comparison between Yb and Sr optical lattice clocks operated in Italy and Japan, respectively. Frequency ratio of the two optical clocks was measured at 2.8×10^{-16} fractional frequency uncertainty, which is the lowest uncertainty of optical lattice clock frequency ratio over 9000 km distance. Effective atmospheric excess path delay calibration with VMF3 atmospheric delay data was one of the keys of the VLBI delay analysis of the single long baseline. In the aspect of geodetic performance, baseline repeatability between the 2.4 m antenna pair achieved the same level with that of IVS R1 and R4 sessions.

1 General Information

VLBI activity of NICT is operated by a group of Space-Time Standards Laboratory (STSL) of National Instate of Information and Communications Technology (NICT). The STSL is keeping Japan Standard Time (JST) at Koganei headquarters in Tokyo, and development of state of art optical lattice clocks is a part of its activity. VLBI group is working at the Kashima Space Technology Center, where two radio telescopes: Kashima 34-m and Kashima 11-m, are located. Driven by the rapid progress of quantum technology, frequency uncertainty of optical lattice clock reaches in order of 10^{-18}. That is exceeding that of microwave emission of Cs atom, which define the ‘second’ as the SI unit of time. Metrological community is planning future re-definition of the ‘second’ with optical frequency standards [1]. Although optical fiber link is the best way for accurate frequency comparison, it does not reach oversea distance. Thus, techniques for long distance frequency link has been required. VLBI technique is also a tool for frequency transfer as the same with GNSS. We have been conducting development of broadband VLBI system for application to intercontinental precise frequency comparison as the main mission. Our broadband VLBI system [2, 3] has similar broad observation frequency range (3.2 GHz - 14 GHz) with VGOS specification [4]. Unique features in our data acquisition system are utilizing originally developed broadband ‘NINJA’ feeds, RF-Direct sampling by 16 GHz sampling rate, and digital filtering. Additionally, Node-Hub Style (NHS) VLBI [3] scheme, which utilizes virtual group delay observable between small antenna pair derived by using closure delay relation, is a challenging approach for geodesy and frequency transfer VLBI.

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2 Activities during the Past Year

Kashima VLBI group of NICT is taking the part of IVS in terms of technology development and observation station by using Kashima 34-m antenna and two 11-m diameter antennas at Kashima and Koganei. Historically, Kashima group had played a pioneering work in the field of VLBI development in Japan. Our developed Japanese K3/K4/K5 VLBI terminal and correlator systems resources have been used by VLBI related Japanese research Institutes.

Activities of analysis center had been performed mostly for the aim of our own VLBI project. Currently, VLBI experiments and data analysis has been conducted for the aim to realize long distance frequency transfer with VLBI observation. Our broadband GALA-V system acquires 4 channels of 1 GHz bandwidth data. Cross correlation processing is made by our GICO3 software correlator [5], then bandwidth synthesis (fringe fitting) of the broadband VLBI data is made by 'komb' [6], respectively. The derived delay and auxiliary data are stored in Mk3 database system via MK3TOOLS [7]. Finally, VLBI data analysis is made by CALC Ver.11.01 and SOLVE Ver.2014.02.21 developed by the NASA/GSFC.

3 Current Status

3.1 VLBI experiments between Italy and Japan with transportable broadband VLBI stations

One of the 2.4 m broadband VLBI station (MARBLE1) was installed in Medicina Radio Astronomical Station of Institute of Radio Astronomy/National Institute for Astrophysics (IRA/INAF) in 2018. A stable reference frequency has been provided to the Medicina station from the Istituto Nazionale di Ricerca Metrologica (INRiM) in Torino, where Ytterbium (Yb) optical lattice clock is operated. Another small antenna (MARBLE2) located at Koganei campus of NICT, where Strontium (Sr) lattice clock is operated, was used for the other end of the experiment. The overview of the frequency link experiment over 9000 km distance is depicted in Figure 1. Fig. 2 shows the block diagram of the frequency link between Yb optical clock in Italy and Sr optical clock in Japan. Several hydrogen masers (H-masers) were used as flywheel to link the frequency chain.

Table 1 lists a series of frequency link VLBI experiments conducted among Medicina, Koganei, and Kashima 34-m antenna. Lack of sensitivity for the small diameter antenna pair was overcome via NHS VLBI scheme by using Kashima 34-m antenna as Hub station. The virtual delay between small antenna pair was analyzed by Calc/Solve with estimating station coordinates, atmospheric zenith delay, and clock parameters. Single clock rate was estimated for each session. The clock rate corresponds to the fractional frequency ratio between two H-masers at each end of the baseline. Atmospheric calibration was a concern in this experiment. Because of sky coverages are limited at each station due to the single long baseline, accurate estimation of atmospheric delay parameter from VLBI data itself was difficult. We took advantage of the Vienna Mapping Function 3 (VMF3) [8] for a priori atmospheric delay correction. The VMF3 data [9] provides dry, wet, and gradient component of zenith delay and their mapping function by 6 hours of interval. We have tested

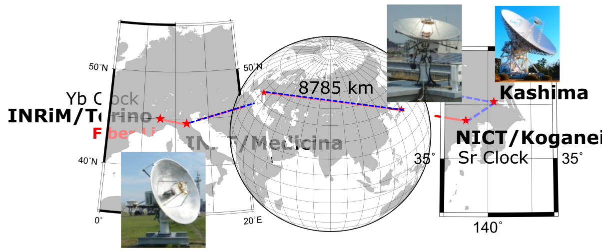

Fig. 1 Overview of the frequency link experiment between Italy and Japan. Reference frequency of Ytterbium lattice clocks operated at INRiM was provided to Medicina (INAF) by fiber link. Frequency link from Medicina to Koganei (NICT) was made by using VLBI observation. Kashima 34-m antenna participated the VLBI experiment to enable VLBI between 2.4 m antenna pair via NHS VLBI scheme.

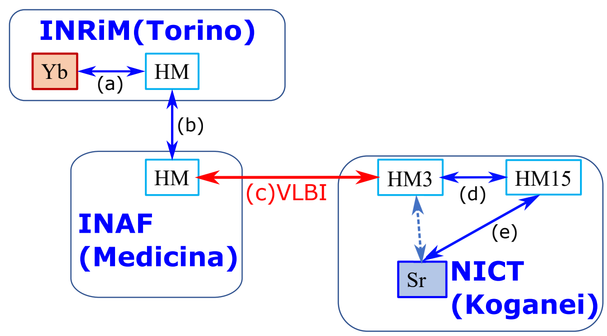

Fig. 2 Block diagram of the frequency chain between INRiM and NICT. Since optical lattice clocks (Yb,Sr) are operated intermittently with several hours of run, hydrogen masers (HM) are used as a flywheel to keep the frequency and link the frequency chain. Frequency ratio between each pair of nodes are measured, and the longest link was made by the VLBI observation.

Table 1 List of experiments conducted by the network of broadband antennas: Kashima 34-m antenna, 2.4 m antenna at Medicina, and 2.4 m antenna at Koganei.

Session Date	Session [hours]	No.Scans (Used/Total)	WRMS residual [ps]
5 Oct. 2018	31.4	1366 / 1470	30
14 Oct. 2018	28.9	1155 / 1415	32
24 Oct. 2018	29.0	— Failure at MBL2 —	
4 Nov. 2018	30.6	1452 / 1645	39
14 Nov. 2018	29.0	1419 / 1539	24
24 Nov. 2018	28.8	1291 / 1435	29
4 Dec. 2018	29.0	1344 / 1511	33
15 Dec. 2018	29.5	1379 / 1470	26
25 Dec. 2018	28.9	1439 / 1501	22
15 Jan. 2019	29.0	1363 / 1437	24
25 Jan. 2019	30.6	1336 / 1591	26
4 Feb. 2019	31.0	1342 / 1500	30
14 Feb. 2019	35.8	1341 / 1585	29
30 May 2019	168.0	1718 / 2088	58
12 Jun. 2019	113.6	1182 / 2168	53
03 Jul. 2019	68.0	1372 / 1421	52
18 Jul. 2019	108.0	1485 / 1530	64
31 Jul. 2019	29.5	1591 / 1667	61

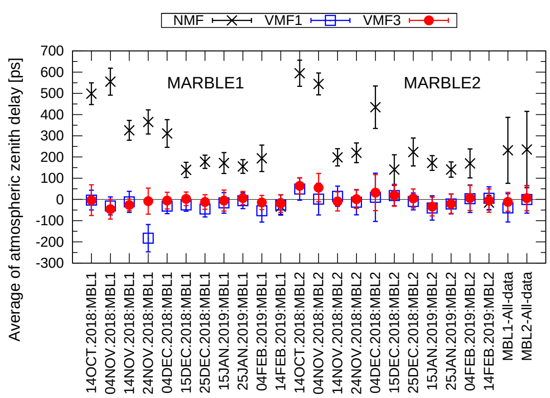

Fig. 3 Session wise average of estimated zenith delay for MARBLE1 and MARBLE2 are compared for three cases of atmospheric a priori calibration with NMF, VMF1, and VMF3.

three cases of atmospheric model, NMF [10], VMF1 [11], and VMF3 for a priori delay correction. Session wise average of the estimated zenith delay residuals are plotted in Fig. 3. The small residuals for VMF1 and VMF3 owes to their accurate atmospheric delay prediction computed by ray tracing technique with numerical weather model of ECMWF (European Centre for Medium-Range Weather Forecasts). Better stability of the VMF3 than VMF1 in the plot will be attribute to

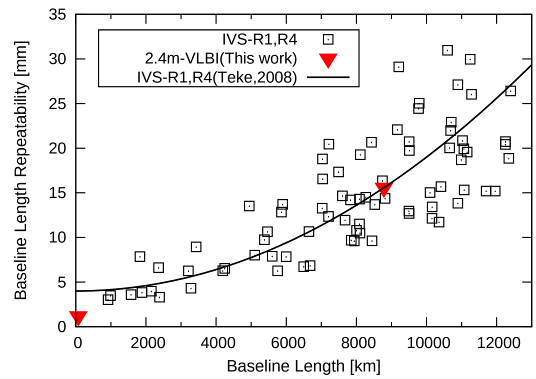

Fig. 4 Baseline repeatabilities of IVS R1/R4 session (squares) in 2011-2013 and 2.4 m antenna pair of broadband VLBI with NHS scheme (red down triangle). Solid line is regression curve by Teke [13].

the advantage of anisotropic modeling of VMF3 by its atmospheric gradient.

3.2 Results in metrology and geodesy

As the results of VLBI frequency link experiment from Oct. 2018 to Feb. 2019, frequency ratio between Yb and Sr lattice clocks was measured with 2.8×10^{-16} fractional frequency uncertainty [12].

Geodetic performance of this experiments was evaluated by comparison to those of IVS R1/R4 sessions in terms of baseline repeatability (BLR). We demonstrated that BLR of 2.4 m antenna pair by NHS scheme was in the same level with the IVS R1 and R4 sessions (Fig. 4).

4 Future Plans

Kashima 34-m antenna, which played the role of a hub station in the experiments, was seriously damaged by strong typhoon Faxai attacked to Japan on 9th September 2019. It was constructed in 1988 as the first Japanese dedicated VLBI radio telescope for ‘Western pacific VLBI network’ project [14]. With consideration of deterioration, the antenna was decided to be dismantled in 2020-2021. Although it became difficult to continue the experiments, the scheme developed in this project can be applied if one of VGOS stations take the role of hub station.

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