NICT VLBI Analysis Center Report for 2019–2020

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Abstract The VLBI analysis activities of NICT target the development and application of broadband VLBI for precise frequency comparison. A pair of small-diameter broadband VLBI stations is used for the nodes of the frequency comparison, and high sensitivity antennas support the VLBI observation by boosting the sensitivity ('Node-Hub' Style: NHS). This NHS VLBI observation scheme was used for the frequency comparison between Yb and Sr optical lattice clocks operated in Italy and Japan, respectively. The frequency ratio of the two optical clocks was measured at a 2.8×10^{-16} fractional frequency uncertainty, which is the lowest uncertainty of optical lattice clock frequency ratio over a 9,000-km distance. Effective atmospheric excess path delay calibrations 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

The VLBI activity at NICT is operated by a group of the Space-Time Standards Laboratory (STSL) of the National Institute of Information and Communications Technology (NICT). The STSL is keeping Japan Standard Time (JST) at the Koganei headquarters in Tokyo, and development of state-of-the-art optical lattice clocks is a part of its activity. The 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, the frequency uncertainty of optical lattice clocks reaches 10^{-18}. This exceeds the microwave emission of Cs atom, which defines the 'second' as the SI unit of time. The metrological community is planning the redefinition of the 'second' with optical frequency standards [1]. Although the optical fiber link is the best way for accurate frequency comparison, it does not reach overseas distances. Thus, techniques for a long distance frequency link have been required.

The VLBI technique is also a tool for frequency transfer, similar to GNSS. We have been conducting the development of a broadband VLBI system for the application to intercontinental precise frequency comparisons as the main mission. Our broadband VLBI system [2, 3] has a similar broad observation frequency range (3.2–14 GHz) as the VGOS specification [4]. Unique features of our data acquisition system include the utilization of the originally developed broadband 'NINJA' feeds, RF direct sampling at a 16-GHz sampling rate, and digital filtering. Additionally, the 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.

2 Activities during the Past Two Years

The Kashima VLBI group of NICT is taking part in IVS in terms of technology development and observa-

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tion stations by using the Kashima 34-m antenna and two 11-m diameter antennas at Kashima and Koganei. Historically, the Kashima group had played a pioneering role 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 the Analysis Center were 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 four channels of 1-GHz bandwidth data. Cross-correlation processing is made by our GICO3 software correlator [5], while 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 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 antennas (MARBLE1) was installed at the Medicina Radio Astronomical Station of the Institute of Radio Astronomy/National Institute for Astrophysics (IRA/INAF) in 2018. A stable reference frequency was provided to the Medicina station from the Istituto Nazionale di Ricerca Metrologica (INRiM) in Turin, where an Ytterbium (Yb) optical lattice clock is operated. Another small antenna (MARBLE2), located at the Koganei campus of NICT where a Strontium (Sr) lattice clock is operated, was used for the other end of the experiment. The overview of the frequency link experiment over a distance of 9,000 km is depicted in Figure 1. Figure 2 shows the block diagram of the frequency link between the Yb optical clock in Italy and the Sr optical clock in Japan. Several hydrogen masers (H-masers) were used as flywheels to link the frequency chain.

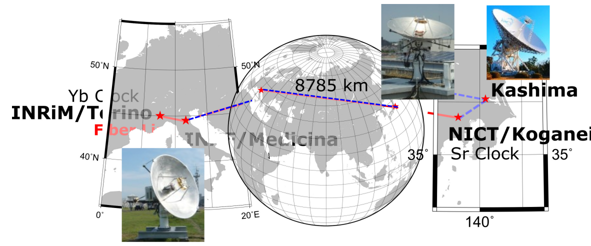

Fig. 1 Overview of the frequency link experiment between Italy and Japan. Reference frequency of Ytterbium lattice clocks operated at INRiM was provided to Medicina (INAF) by fiber link. Frequency link from Medicina to Koganei (NICT) was made by using VLBI observation. Kashima 34-m antenna participated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

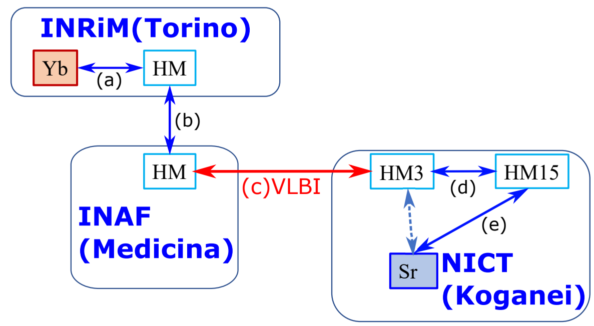

Fig. 2 Block diagram of the frequency chain between INRiM and NICT. Since optical lattice clocks (Yb, Sr) are operated intermittently with several hours of run, hydrogen masers (HM) are used as a flywheel to keep the frequency and link the frequency chain. Frequency ratios between each pair of nodes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

Table 1 lists a series of frequency link VLBI experiments conducted between Medicina, Koganei, and the Kashima 34-m antennas. The lack of sensitivity of the small-diameter antenna pair was overcome via the NHS VLBI scheme by using the Kashima 34-m antenna as a Hub station. The virtual delay between the small antenna pair was analyzed by Calc/Solve with estimating station coordinates, atmospheric zenith delay, and clock parameters. A 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 sky coverages are limited at each station due to the single long baseline, accurate estimation of the atmospheric

Table 1 List of experiments conducted by the network of broadband antennas: the 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

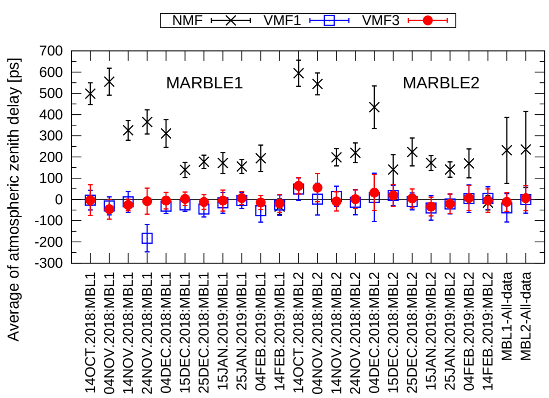

Fig. 3 Session-wise average of estimated zenith delay for MARBLE1 and MARBLE2 for three cases of atmospheric a priori calibration (with NMF, VMF1, and VMF3).

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 components of zenith delay and their mapping function by six hours of interval. We have tested three atmospheric models (NMF [10], VMF1 [11], and VMF3) for the a priori delay correction. The session-wise average of the estimated zenith delay residuals are plotted in Figure 3. The small residuals for VMF1 and VMF3

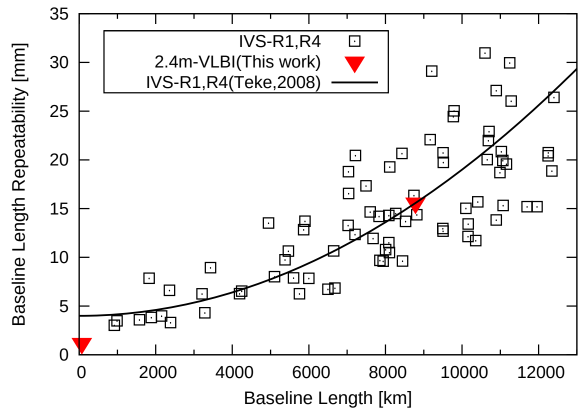

Fig. 4 Baseline repeatabilities of IVS R1/R4 session (squares) in 2011–2013 and the 2.4-m antenna pair of broadband VLBI with NHS scheme (red down triangle). The solid line is regression curve by Teke [13].

is owing to their accurate atmospheric delay prediction computed by the ray tracing technique with numerical weather models of the ECMWF (European Centre for Medium-Range Weather Forecasts). Better stability of the VMF3 than VMF1 in the plot is attributed to the advantage of anisotropic modeling of VMF3 by its atmospheric gradient.

3.2 Results in Metrology and Geodesy

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

The geodetic performance of these experiments was evaluated by comparing them to the IVS R1/R4 sessions in terms of baseline repeatability (BLR). We demonstrated that BLR of the 2.4-m antenna pair by the NHS scheme was at the same level as the IVS R1 and R4 sessions (Figure 4).

4 Future Plans

The Kashima 34-m antenna, which played the role of a hub station in the experiments, was seriously damaged by strong typhoon Faxai on 9 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 its deterioration, it was decided to dismantle the antenna in 2020–2021. Although it became difficult to continue the experiments, the scheme developed in this project can be applied if one of the VGOS stations takes the role of hub station.

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References

1. Riehle F., "Towards a Re-definition of the Second Based on Optical Atomic Clocks", Comptes Rendus Physique, Vol. 16, 5, 2015, pp. 506–515, https://doi.org/10.1016/j.crhy.2015.03.012, 2015.
2. Sekido M., et al., "Broadband VLBI System GALA-V and Its Application for Geodesy and Frequency Transfer", Proceedings of 23rd European VLBI for Geodesy and Astrometry Meeting, pp. 5–9, 2017.
3. Sekido M., et al., "Broadband VLBI system using transportable stations for geodesy and metrology: an alternative approach to the VGOS concept", J. Geodesy, https://doi.org/10.1007/s00190-021-01479-8, 2021.
4. Petrachenko, B., et al., "Design Aspects of the VLBI2010 System", Progress Report of the VLBI2010 Committee. NASA Technical Memorandum, NASA/TM-2009-214180, June 2009.
5. Kimura, M., "Development of the software correlator for the VERA system II", IVS NICT-TDC News 35, pp.22-25, http://www2.nict.go.jp/sts/stmg/ivstdc/news_28/pdf/tdcnews_28.pdf, 2007.
6. Kondo, T., and K. Takefuji, "An algorithm of wideband bandwidth synthesis for geodetic VLBI", Radio Sci., 51, doi:10.1002/2016RS006070, 2016.
7. Hobiger T., Y. Koyama, and T. Kondo, "MK3TOOLS & NetCDF - storing VLBI data in a machine independent array oriented data format", Proceedings of the 18th European VLBI for Geodesy and Astrometry Work Meeting, ISSN 1811-8380, pp. 194-195, 2007.
8. Landskron1 D., J. Böhm1, "VMF3/GPT3: refined discrete and empirical troposphere mapping functions", J. Geod. 92:349–360, https://doi.org/10.1007/s00190-017-1066-2, 2018.
9. re3data.org, "VMF Data Server; re3data.org - Registry of Research Data Repositories", editing status 2019-01-15, https://doi.org/10.17616/R3RD2H, 2019.
10. Arthur. E. Niell, "Global mapping functions for the atmosphere delay at radio wavelengths", J. Geophys. Res. , 101, pp. 3227–3246, https://doi.org/10.1029/95JB03048, 1996.
11. Johannes Böhm, Birgit Werl, and Harald Schuh, "Troposphere mapping functions for GPS and VLBI from ECMWF operational analysis data", J. Geophys. Res. 111, B02406, https://doi.org/10.1029/2005JB003629, 2006.
12. Pizzocaro M., et al., "Intercontinental comparison of optical atomic clocks via very long baseline interferometry", Nat. Phys., http://doi.org/10.1038/s41567-020-01038-6, 2020.
13. Teke K., R. Heinkelmann, & J. Böhm, "VLBI baseline length repeatability tests of IVS-R1 and IVS-R4 session types", IVS 2008 General Meeting Proceedings "Measuring the Future", http://ivscc.bkg.bund.de/publications/gm2008/teke.pdf, 2008.
14. Imae M., et al., "Overview of the experiment system: The main VLBI station at Kashima", J. Commun. Res. Lab., 42:1 pp. 5–14, https://www.nict.go.jp/publication/journal/42/001/Journal_Vol42_No001_pp003-110.pdf, 1995.