NICT VLBI Analysis Center Report for 2017–2018

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Abstract The VLBI analysis activities at NICT focus on the development and application of broadband VLBI for precise frequency comparisons. A pair of small diameter broadband VLBI stations and a high sensitivity antenna have been jointly used to derive broadband group delays between the small antenna pair by using the closure delay relation (‘Node-Hub’–style VLBI). This Node-Hub–style VLBI was verified in domestic experiments for frequency comparisons between NMIJ and NICT. Then one of the small antennas was transported to Medicina station in Italy in 2018, and VLBI experiments for optical clock comparisons have started.

1 General Information

The Space-Time Standards Laboratory (STSL) of the National Institute of Information and Communications Technology (NICT) has been conducting broadband VLBI system development for application to intercontinental precise frequency comparisons. The VLBI group of NICT is working at the Kashima Space Technology Center, where two radio telescopes, Kashima 34-m and Kashima 11-m, are located. We developed a broadband VLBI system named GALA-V [1], which has a similarly broad observation frequency range (3.2–14 GHz) as VGOS [2]. Unique features of our data acquisition system utilize the originally developed broadband ‘NINJA’ feeds and the RF-Direct sampling with a 16-GHz sampling rate and following digital filtering. Additionally, Node-Hub–style VLBI [4], which utilizes group delay observables between a small antenna pair using the closure delay relation, is a challenging approach for geodetic VLBI and frequency transfer.

NICT/ Kashima Space Technology Center

NICT Analysis Center

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This report describes the activities of the VLBI analysis in NICT’s VLBI group, focusing on the analysis for geodesy and frequency transfer with the broadband VLBI system.

2 Component Description

NICT is in charge of keeping and supplying national Japanese Standard Time (JST) and standard frequency traceable to the ‘second’ of the International System of Units (SI). The current definition of the ‘second’ of time is made by using the microwave emission of the Cs atom. This is expected to be replaced by a new definition using a more accurate optical frequency emission of a certain kind of atom in the near future [5]. Several kinds of atoms are investigated as candidates for the new definition. Then, an accurate frequency comparison technique between different optical frequency standards is required, especially one that can be used over intercontinental distances. Based on this background, the VLBI application for frequency transfer is the mission of the VLBI group at NICT. The observation scheme of a VLBI session for clock comparison is basically identical to a standard VLBI session for geodesy. We have decided to use transportable, small-diameter telescopes as nodes for the frequency comparison; they need to be installed at a metrological institute where an optical frequency standard is operated as the subject of comparison.

Here, a VGOS-like broadband VLBI system brings two benefits: 1) enhancement of the signal-to-noise ratio (SNR) by an increased number of samples, and 2) improvement in precision of group delay measurement via one order wider observation frequency range with respect to conventional VLBI system using S/X band receivers. The correlation amplitude of VLBI is proportional to the geometrical mean of the aperture area of two antennas. Thus, the combined use of a small antenna with a high sensitivity antenna enables the small antenna to function as a node of an interferometer. Due to the increased SNR and delay precision, a transportable small VLBI station can be used as the node for frequency comparisons on intercontinental baselines.

The GALA-V [1] system acquires four channels at 1-GHz bandwidth. Cross-correlation processing and post-processing (fringe-fitting) of the broadband VLBI data is made by the GICO3 [6] software correlator and the wideband bandwidth synthesis software 'komb' [7], respectively. The derived delay observable and auxiliary data are stored in a Mk3 database using MK3TOOLS [8]. VLBI data analysis has been made with CALC Ver. 11.01 and SOLVE Ver. 2014.02.21 developed at NASA/GSFC.

3 Staff

Members who are contributing to the Analysis Center at NICT are (in alphabetical order):

- KONDO Tetsuro: Development of broadband bandwidth synthesis software 'komb'.
- SEKIDO Mamoru: Coordination of broadband VLBI observations and in charge of data analysis with CALC/SOLVE.
- TAKEFUJI Kazuhiro: Maintaining and operating the correlation software 'GICO3' for broadband data processing.

4 Activities during 2017–2018

4.1 Testing GALA-V System in Domestic Network

The concept of the GALA-V project based on 'Node-Hub'–style VLBI is displayed in Figure 1. When the observed radio source is a point source, the circular sum of the time delay, which is the arrival time difference of an identical wavefront at each station, of a closed triangle becomes zero. By using this closure delay relation, the delay observable ($\tau_{\rm AB}$) between the small diameter antenna pair (AB) is computed by the linear combination of the delays ($\tau_{\rm RA}$, $\tau_{\rm RB}$) of the small and the large diameter baselines (RA, RB). Because the time tag of the delay is defined as the signal arrival epoch at station $\mathbf{X}$ of baseline $\mathbf{XY}$, the closure delay is given by the following formula with better than one picosecond accuracy on any baseline on the earth:

$$
\begin{aligned}
&\tau_{\rm AB}(t_{\rm prt}) \\
&= \tau_{\rm RB}(t_{\rm prt} - \tau_{\rm RA}(t_{\rm prt})) - \tau_{\rm RA}(t_{\rm prt} - \tau_{\rm RA}(t_{\rm prt})) \\
&\cong \tau_{\rm RB}(t_{\rm prt}) - \tau_{\rm RA}(t_{\rm prt}) - \frac{d}{dt}\tau_{\rm AB}(t_{\rm prt}) \times \tau_{\rm RA}(t_{\rm prt}),
\end{aligned} \tag{1}
$$

where $t_{\rm prt}$ is the reference epoch of the delay data.

A transportable broadband VLBI station with a 1.6-m diameter antenna and equipped with a high speed data acquisition system was installed at the

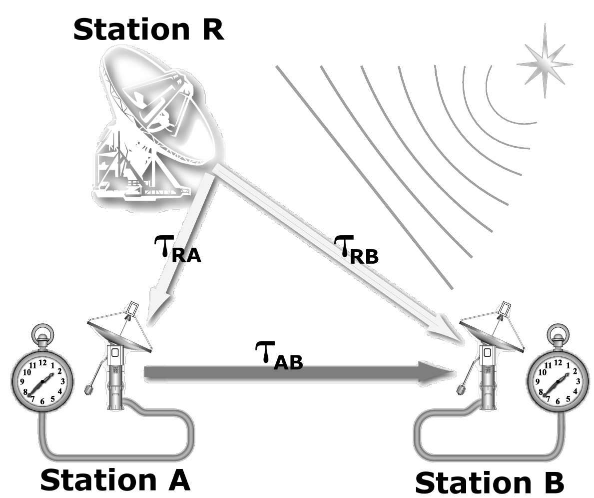

Fig. 1 The concept of the 'Node-Hub'–style VLBI by combination use of transportable, small-diameter VLBI stations and a high sensitivity antenna.

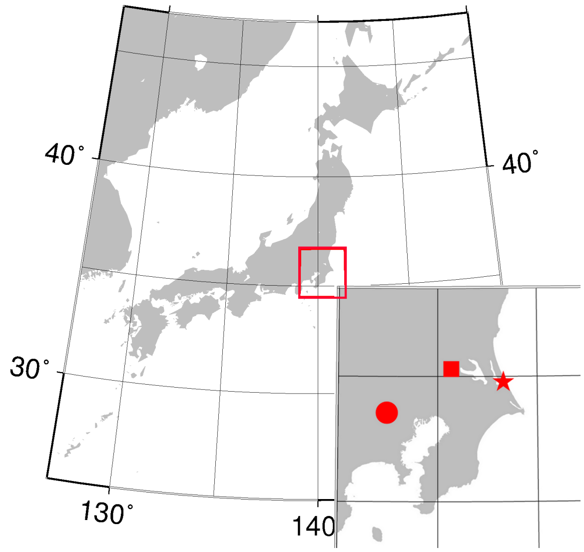

Fig. 2 Location of the small broadband VLBI stations MARBLE1 (■) at NMIJ and MARBLE2 (●) at NICT Headquarters as well as the Kashima 34-m antenna (★).

Table 1 Broadband VLBI experiments conducted in 2017–2018. Abbreviation of station names are as follows: Kas34: Kashima 34-m antenna, MBL1: MARBLE1 2.4-m diameter antenna at NMIJ, MBL2: MARBLE2 2.4-m diameter station at NICT Koganei, OTNE: Onsala Twin Telescope North East.

Session Date	Stations	No. Scans (Used/Total)	Session Length
13-14 Jan. 2017	Kas34-MBL2	110/110	21 hours
21-23 Apr. 2017	Kas34-MBL1-MBL2	1707/1722	49.5 hours
12-13 May 2017	Kas34-MBL1-MBL2	948/1210	28 hours
09-12 Jun. 2017	Kas34-MBL1-MBL2	2237/2284	64.7 hours
03-06 Jul. 2017	Kas34-MBL1-MBL2	2120/2182	70 hours
10-14 Aug. 2017	kas34-MBL1-MBL2	Failed	77.5 hours
25-28 Aug. 2017	Kas34-MBL1-MBL2	Failed	66 hours
11-13 Nov. 2017	Kas34-MBL1-MBL2	Failed	60 hours
18-20 Dec. 2017	Kas34-MBL1-MBL2	1222/1231	40 hours
22-23 Dec. 2017	Kas34-MBL1-MBL2	998/1011	30 hours
26-27 Dec. 2017	Kas34-MBL1-MBL2	1087/1175	33 hours
03-05 Jan. 2018	Kas34-MBL1-MBL2	Failed	42 hours
12-13 Jan. 2018	Kas34-MBL1-MBL2	826/864	50 hours
18-21 Jan. 2018	Kas34-MBL1-MBL2	1431/2444	69.5 hours
31-28 Jan. 2018	Kas34-OTNE	1431/2444	17 hours
27-28 Mar. 2018	Kas34-OTNE	158/199	17 hours

National Meteorology Institute of Japan (NMIJ) in Tsukuba in 2014. Another 1.5-m diameter antenna is located at NICT Headquarters in Koganei, Tokyo. These small antennas were originally designed with prime focus optics. In 2016 and 2017, these antenna systems at NICT and NMIJ were replaced by 2.4-m diameter Cassegrain focus optics.

NMIJ and NICT are the national institutes that keep the time series UTC (NMIJ) and UTC (NICT), respectively. And their time data is routinely reported to BIPM (Bureau International des Poids et Mesures). Thus, frequency comparisons between UTC (NMIJ) and UTC (NICT) are possible in multiple ways other than VLBI. For this it is a good testbed to examine the performance of our VLBI frequency link.

In March 2017, the antenna system of MARBLE1 was replaced with a 2.4-m diameter Cassegrain focus optics. A series of test VLBI sessions were conducted in 2017 as shown in Table 1. The longer the session, the better the frequency comparison. This is the reason for session lengths longer than 24 hours, which is the standard geodetic VLBI session length. In August 2017, the optical fiber cable at MARBLE2 broke. It was subsequently repaired by using a spare fiber cable. Another issue with the stability of the wideband optical RF signal transmission system occurred at MABLE1. It was mended by replacing the optical signal transmission system from a Sumitomo E18000 to a FiberOptic TX:10341C/Rx:10458E.

As described above, we are testing Node-Hub–style VLBI, which uses a delay observable derived from the linear combination based on closure delay relation. The closure delay relation is affected if the radio source has structure [9]. Since its influence becomes larger as the baseline becomes longer, it does not have a significant effect in VLBI experiments using domestic short baselines ($\leq$ 100 km). One of the benefits of the Node-Hub–style VLBI is the cancellation of the delay variation introduced by large diameter antenna. We have confirmed the benefit of the new VLBI observable approach on this baseline. The improvement of the delay residual by using this technique is described in the NICT Analysis Center report for 2015–2016 [10].

4.2 Clock Comparison between UTC (NMIJ) and UTC (NICT)

We conducted a series of experiments from 18 December 2017 to 3 January 2018 with about four days interval. A comparative evaluation of the frequency transfer performance was made between different techniques.

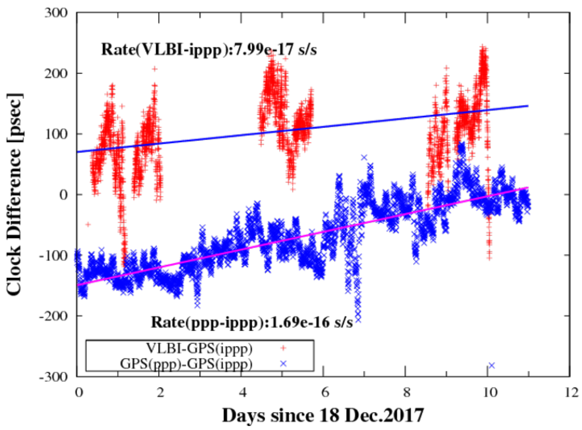

Fig. 3 Comparison of frequency techniques by double difference between VLBI–IPPP and PPP–IPPP.

Data for UTC (NMIJ)–UTC (NICT) from Precise Point Positioning (PPP) processing of GPS data is available from the FTP site of BIPM. In addition, courtesy of G. Petit and J. Leute of BIPM, frequency comparison by integer PPP (IPPP) processing of GPS data, which has a 1^{-16} precision for frequency transfer [11], was provided for the evaluation of the VLBI frequency link. Double difference data of UTC (NMIJ)–UTC (NICT) for the pairs of VLBI–IPPP and PPP–IPPP are plotted in Figure 3. This data shows that the VLBI frequency link has the potential to give a more accurate frequency transfer than PPP processing of GPS data. Phase ambiguity is a potential cause of wrong delay derivation in the case of GPS using carrier phase. Long-term stability of VLBI data in terms of clock comparison is thought to be based on the fact that VLBI uses the group delay observable instead of phase. Especially in the case of broadband VLBI, the absolute delay is obtained without ambiguity.

4.3 Other Activities

Space Geodesy Software C5++ : Space geodesy analysis software package “C5++” [12][1], was developed under multi-organization collaborations. M. Sekido is taking part in the development and keeping maintenance of the software.

MK3TOOLS : Software package MK3TOOLS is a package of platform independent VLBI database read and write software originally developed by T. Hobiger. Currently T. Hobiger at the University of Stuttgart in Germany and M. Sekido of NICT are jointly maintaining the package. MK3TOOLS is freely available from the Web at http://hg.hobiger.org/MK3TOOLS/.

[1] http://www2.nict.go.jp/sts/stmg/www3/c5++/

5 Future Plans

We have started broadband VLBI experiments for optical clock comparisons in collaboration with the Istituto Nazionale di Ricerca Metrologica (INRiM), National Institute for Astrophysics (INAF), and NICT. Node-Hub–style VLBI using closure delay relation is tested on this over 8000-km baseline.

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References

1. Sekido M., et al., “Broadband VLBI System GALA-V and Its Application for Geodesy and Frequency Transfer”, Proceedings of 23th European VLBI for Geodesy and Astrometry Meeting, pp. 5–9, 2017.
2. 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.
3. Takefuji K, et al., “High-order Sampling Techniques of Aliased Signals for Very Long Baseline Interferome-

try", PASP 124 pp.1105-1112, https://doi.org/10.1086/668232, 2012.

4. Sekido, M., "'Node - HUB' Style VLBI with Broadband System", IVS NICT-TDC News. No. 37, pp. 22–25, http://www2.nict.go.jp/sts/stmg/ivstdc/news_37/pctdc_news37.pdf, 2017.
5. Riehle F., "Towards a Re-definition of the Second Based on Optical Atomic Clocks", https://doi.org/10.1016/j.crhy.2015.03.012, Comptes Rendus Physique, Vol. 16, 5, 2015, pp. 506–515, 2015.
6. 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.
7. Kondo, T., and K. Takefuji, "An algorithm of wideband bandwidth synthesis for geodetic VLBI", Radio Sci., 51, doi:10.1002/2016RS006070, 2016.
8. 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.
9. Ming H. Xu, et al., "The impacts of source structure on geodetic parameters demonstrated by the radio source 3C371", J. Geod., 91, 767, https://doi.org/10.1007/s00190-016-0990-x, 2017.
10. Sekido M., "NICT VLBI Analysis Center Report for 2015-2016", in International VLBI Service for Geodesy and Astrometry 2015+2016 Biennial Report, edited by K. D. Baver, D. Behrend, and K. L. Armstrong, NASA/TP-2017-219021, pp. 241–244, 2017.
11. Petit. G., et al., "1×10^{-16} frequency transfer by GPS PPP with integer ambiguity resolution", Metrologia 52 301.309, doi:10.1088/0026-1394/52/2/301, 2015.
12. Hobiger, T., et al., "c5++ - Multi-technique Analysis Software for Next Generation Geodetic Instruments", IVS 2010 General Meeting Proceedings - VLBI2010: From Vision to Reality, NASA/CP-2010-215864, pp. 212–216, 2010.