NICT VLBI Analysis Center Report for 2015–2016

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Abstract The VLBI analysis activity of NICT is focusing on distant clock comparisons with small diameter broadband stations. Broadband VLBI observations between small and large diameter stations have become available. A series of domestic broadband VLBI sessions have been conducted in 2016. The broadband VLBI data showed advanced precision even with small diameter antennas. A signal processing path has become available from VLBI observation, correlation processing, bandwidth synthesis, registration to Mk3DB, up to VLBI analysis with CALC/SOLVE. We could show that the broadband delay observable has sufficient precision even with small diameter stations. Further improvement of VLBI analysis will depend on how much we could reduce atmospheric excess delay by observation strategy.

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 and observations with it. The VLBI group is located at the Kashima Space Technology Center. A research subject of the VLBI group of NICT is the application of the VLBI technique in precision frequency comparisons over intercontinental distances. The broadband VLBI system named GALA-V, which is compatible with VGOS specifications [1], has been developed for this application. The VLBI observation scheme for clock comparisons is basically the same as for standard geodetic VLBI sessions except that the session length is not limited to 24 hours, but it can last as long as 48–62 hours or more. Since our VLBI analyses have been performed mainly for technology development, this report focuses on the analysis for geodesy and time-and-frequency transfer with the broadband VLBI system.

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2 Component Description

The VLBI application for frequency transfer is the current mission of our project, and the clock parameters estimated by VLBI sessions are the products as the clock difference between two VLBI stations. The observation strategy of a VLBI session for clock comparison is basically the same as for a standard VLBI session for geodesy. To get a better separation of the estimation parameters, observations are made of extragalactic radio sources in different directions in the sky by frequent switching. Broadband VLBI observations with GALA-V [2] acquire four channels of 1-GHz bandwidth data. Cross correlation processing of the broadband VLBI data is made by the GICO3 [3] software correlator, and the results are stored in Mark III databases through a data conversion with MK3TOOLS [4]. Then VLBI data analysis package CALC Ver.11.01 and SOLVE Ver.2014.02.21 developed by NASA/GSFC is used for the data analysis.

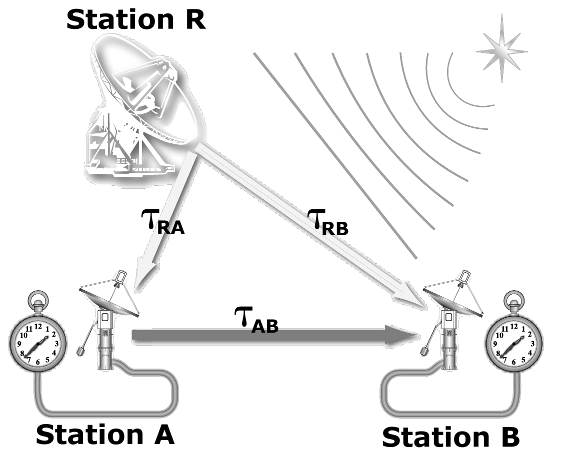

Fig. 1 The concept of the distant frequency comparison project GALA-V is composed of a pair of small-diameter antennas and one large-diameter antenna. Transportable small-diameter antennas are placed in laboratories, where the atomic frequency standards to be compared are located. The sensitivity of the VLBI observation between a pair of small-diameter antennas is boosted by joint observation with large-diameter antennas.

3 Staff

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

- KONDO Tetsuro: Maintenance of correlation software K5VSSP and development of broadband bandwidth synthesis software.
- SEKIDO Mamoru: Coordinating VLBI observing and making data analysis with CALC/SOLVE.
- TAKEFUJI Kazuhiro: Data processing of broadband data and development of broadband VLBI observation system.

4 Activities during the Past Years

4.1 Frequency Transfer by Means of VLBI

Space-geodetic techniques such as GNSS have been proven to be useful tools for time and frequency transfer purposes. VLBI is another space-geodetic technique that can be utilized for frequency transfer. In contrast to GNSS, VLBI does not require any orbital information. It directly refers to an inertial reference frame defined by the location of the quasi-stellar objects. Being free from the availability of communication satellites and its transponder rental cost are further advantages of VLBI with respect to the two-way satellite time and frequency transfer (TWSTFT) technique.

The concept of our project (GALA-V) is displayed in Figure 1. Transportable small-diameter antennas are placed in laboratories, where atomic frequency standards to be compared are located. A sufficient signal to noise ratio (SNR) is gained by joint observations with small and large-diameter antennas. By using the closure relation of delay, the VLBI delays for the pair of small diameter antennas are derived, and the delay data are stored in Mark III databases and analyzed.

The delay observable ($\tau_{\rm AB}$) between the small diameter antenna pair (AB) is computed by linear combination of those ($\tau_{\rm RA}$ and $\tau_{\rm RB}$) of the small and large diameter baselines (RA and RB) as follows:

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

where $t_{\rm prt}$ is the reference epoch of the observation. Radio source structure affecting the closure relation is subject to being investigated, and that is in the scope of our research.

One of the small-diameter antennas equipped with a broadband feed and high speed data acquisition system was installed at the National Meteorology Institute of Japan (NMIJ) in Tsukuba in 2014. Another small antenna is located at NICT Headquarters in Koganei, Tokyo. Both NMIJ and NICT are the national institutes engaged in the development of atomic frequency standards and are keeping the time series of UTC(NMIJ) and UTC(NICT), respectively.

By development of original broadband feeds, the IGUANA-H [6] and NINJA feeds, two small antennas and the Kashima 34-m antenna were upgraded to allow for broadband observations and have had their sensitivity improved step by step. Broadband bandwidth synthesis software has been developed [7] to derive precise delay observables from four bands of 1 GHz wide data.

In 2016, four bands of 1 GHz width of data acquisition became ready at our three stations, and the signal path from observation to data analysis has become available. A series of test VLBI sessions conducted in 2016 are listed in Table 1. Unlike with standard VLBI sessions, the session length is as long as 48–62 hours

Table 1 Broadband VLBI experiments conducted in 2016. The abbreviations of station names are as follows: Kas34: Kashima 34-m antenna, MBL1: MARBLE1 1.6-m diameter antenna at NMIJ, MBL2: MARBLE2 2.4-m diameter station at NICT Koganei.

Session Date	Stations	No.Scans (Used/Total)	Session Length
26-27 Jan.	Kas34-MBL1-MBL2	1330/1500	46 hours
12-13 Feb.	Kas34-MBL1-MBL2	1250/1600	47 hours
28-29 Feb.	Kas34-MBL1-MBL2	1050/1450	49 hours
16-17 May	Kas34-MBL1-MBL2	1220/1410	31 hours
24-25 Jun.	Kas34-MBL1-MBL2	1800/1850	49 hours
10-11 Jul.	Kas34-MBL1-MBL2	1960/2003	48 hours
23-24 Aug.	Ish13-MBL1-MBL2	1372/1385	43 hours
12-13 Sep.	Ish13-MBL1-MBL2	1600/1640	35 hours
25-28 Nov.	Kas34-MBL1-MBL2	2193/2237	62 hours
09-12 Dec.	Kas34-MBL1-MBL2	2022/2063	62 hours

because the project target is monitoring the clock difference.

The post-fit residuals and a histogram of the residuals of the VLBI session on 25–28 November are displayed in Figure 2. The residual plot in panel (a) was made by analysis of the A(NMIJ)-B(NICT) baseline, whose delay data were derived by equation (1) from delay data of the R(Kashima34)-A and the R-B baselines. The weighted RMS of the residuals was 14.2 ps in this case. Figure 2 (b) shows the histograms of residuals for the AB baseline and the RA and RB baselines. Because the delay observable of the AB baseline is computed by linear combination of the delay observable for RA and RB, the error of the delay observable is the root-sum-square of that of the RA and RB baselines by error propagation law. However, the histogram plot shows that the error residual distribution of the AB baseline data does not extend with respect to those of the RA and RB baselines. This suggests that the broadband delay observable is sufficiently precise, and the residual as an indicator of the analysis error is dominated by other causes, which is thought to be the uncertainty of the atmospheric delay.

We assume that the measurement data of the clock difference is the estimated clock parameter plus the residuals of VLBI analysis. The clock difference between UTC(NMIJ)-UTC(NICT) obtained by the VLBI session of 25–28 November is plotted in Figure 3 (a). The clock difference measured by GPS observations provided from BIPM is plotted also. The absolute difference between the clocks is difficult to measure for VLBI; then the offset of the vertical position of VLBI

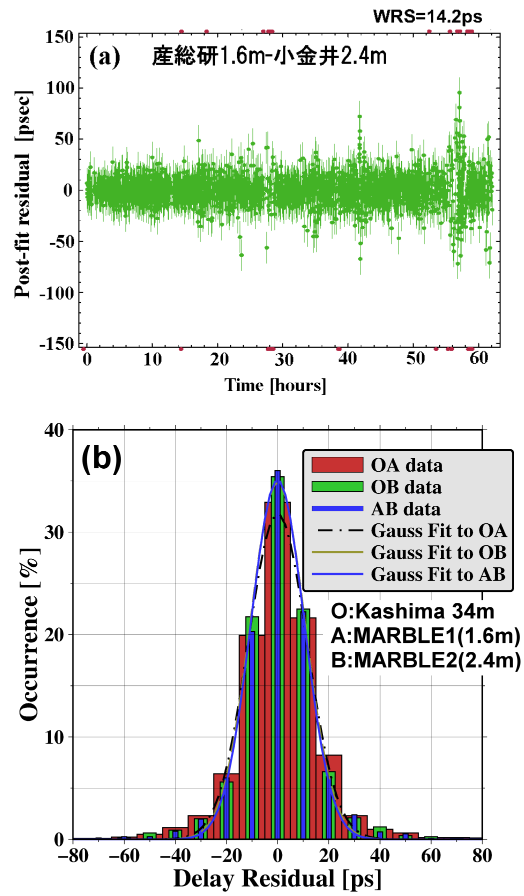

Fig. 2 (a) Post-fit residuals of the VLBI session on 25–28 November for the NICT–NMIJ baseline. (b) Histograms of the distribution of residuals are plotted for the AB and RA, RB baselines.

data in Figure 3 (a) is adjusted to be appropriate for comparison with GPS data. The Allan standard deviation computed from each of the time series and their differences are displayed in panel (b). Because the true clock difference is not known, we cannot say which technique has better performance from the data, although it is proven that VLBI observations between a pair of small diameter antennas works for clock comparisons with a performance no worse than that of GPS.

4.2 Other Activities

Space Geodesy Software Package C5++: The analysis software package for Space Geodesy (SLR,

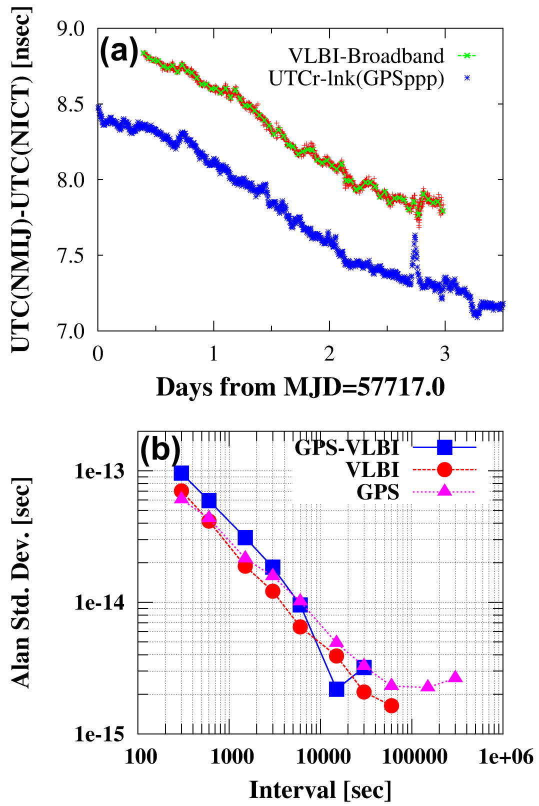

Fig. 3 The clock difference series between NICT and NMIJ compared by VLBI('×') and GPS('*') observations are plotted in panel (a). Allan standard deviation of each time series and their differences are plotted in panel (b).

VLBI, and GNSS) "C5++" [5], has been conducted under multi-organization collaborations. NICT is taking a part in the development and maintenance of the software.

MK3TOOLS: Software package MK3TOOLS, which is a platform-independent VLBI database format with NetCDF, was originally developed by T. Hobiger during his stay at NICT. Currently T. Hobiger at Chalmers Univ. of Tech. of Sweden and M. Sekido of NICT are jointly maintaining the package.

5 Future Plans

We are going to continue broadband VLBI sessions using domestic baselines. After we can confirm the performance and the stability of the system, we are willing to export one of the small VLBI stations to foreign institutes to test and evaluate the performance of GALA-V system for distant clock comparison.

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