Development Status of GALA-V Broadband VLBI — Geodetic Solution and Clock Comparison –

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Abstract: Development of broadband VLBI system named GALA-V has been conducted by NICT for VLBI application to distant frequency transfer. Observation systems and signal chain from data acquisition to analysis has become ready. A series of broadband VLBI sessions with pair of small diameter antennas and high sensitivity antenna (Kashima 34m or Ishioka 13m) have been performed since Jan. 2016. VLBI delay data on the baseline between small antenna pair were not directly derived by the cross correlation of this data set, but that was computed by linear combination of delay observables between small antennas and high sensitivity antenna baselines. Geodetic solutions of seventy km baseline between 1.6m and 2.4m diameter antennas were obtained by the virtual observables. The respectability of the station coordinates were several millimeters in horizontal and a few centimeter in vertical position. Atomic clock behaviors between two small stations are obtained from these VLBI sessions and they are consistent with those derived by GPS observations. This paper reports overview of the system development and data analysis results of broadband VLBI sessions in 2016.

1. Introduction

NICT is conducting development of broadband VLBI system named GALA-V for distant frequency transfer [1]. Broad observation frequency range 3-14 GHz has been motivated for improvement in sensitivity and delay measurement precision, and joint observations with VGOS stations are in the scope. The GALA-V system has target of making distant frequency comparison between transportable small VLBI stations by the help of joint observation with high sensitivity VLBI stations. Advantages of using small antennas are mainly two folds. Firstly, lower cost and mobility to installation to atomic time standard laboratory is suitable for a frequency transfer tool. Secondary, large diamter antenna has potential cause of delay fluctuation such as distortion of antenna structure and long signal transmission lines. Those effects related with large diamter antenna are canceled out in the liniear conbination of the equation (1). Magnitude of distortion is smaller for small antenna, thus potential cause of error sources are reduced.

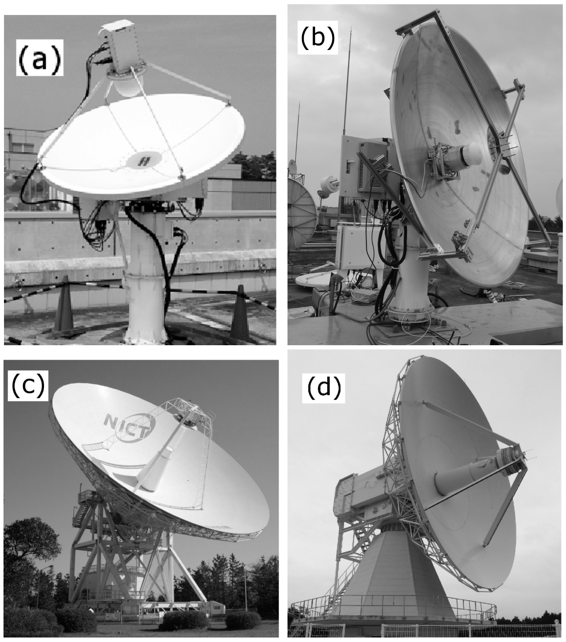

Figure 1. Pictures of VLBI antennas, which are capable of broadband observation in Japan. (a) MARBLE1 1.6m, (b)MARBLE2 2.4m, (c) Kashima 34m, (d) Ishioka 13m.

Signal to noise ratio (SNR) of VLBI observation is proportional to the products of two observing stations of the baseline. Thus disadvantage of lower sensitivity of small antenna pair (A and B) is compensated by joint observation with high sensitivity station (R). Even SNR was not enough on A-B baseline, as far as R-A and R-B baselines works as interferometer, delay observable of small antenna pair τ_{AB} can be computed by linear combination of delay observable $\tau_{\rm RA}$, $\tau_{\rm RB}$ as follows:

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

It should be noted that this is only valid when the radio source is supposed as a point source with respect to the fringe spacing formed by the projected baseline. Radio source structure effect have to be considered when the brightness distribution of the radio source is not negligible. We can use this assumption for the experiments described in this paper due to short baselines.

Based on this idea, broadband VLBI stations and high speed data acquisition systems have been developed. Fig. 1 shows VLBI stations, which is capable of broadband observation in Japan. Kashima 34m station and small diameter broadband stations MARBLE1 and MARBLE2 have become ready for operational broadband observations in 2016. Ishioka 13m station of Geospatial Information Authority of Japan (GSI) has started its operation since 2015. This report will describe current status of broadband system development, and some results of broadband VLBI sessions conducted in 2016.

2. Development of Broadband VLBI System GALA-V

2.1 Broadband VLBI Antennas

Kashima 34 m diameter VLBI station was upgraded by installation of our original broadband feed systems. The first prototype feed IGUANA-H, which has sensitivity at 6.5-15 GHz[2, 3], was installed in 2014. The next feed NINJA was designed for 3.2-14.4 GHz frequency range[4], and it was mounted on the 34 m antenna in 2015. System temperature and System Equivalent Flux Density (SEFD) are about 200-300 Kelvin and 1500-2000 Jansky for 3-11GHz frequency range, respectively[5].

A pari of small diamter antennas MARBLE1 and 2 are originally developed for the project of baseline evaluation[6]. Both of these antennas were using Rindgren Quadridge Flared Horn (QRFH)s and room temperature LNAs with frequency downconverter for S/X-band in that project. We have upgraded them to enable broadband observation for GALA-V project. One of two broadband transportable antennas (MARBLE1 of 1.6m diameter) has been installed at National Institute of Metrology in Japan (NMIJ) at Tsukuba. And the other one (MARBLE2 of 1.5m diameter) has been placed at NICT headquarter at Koganei.

MARBLE2 1.5 m diameter prime focus antenna using QRFH has been upgraded to 2.4 m dish of Cassegrain optics with second NINJA feed in 2016. By using room temperature LNA, the system noise temperature is around 150-200 Kelvins in 3-11 GHz frequency range. Now we are working for tuning and evaluation of NINJA feed at MARBLE2. After that evaluation, the third NINJA feed will be installed to MARBLE1 antenna, and it will be upgraded to 2.4 m diameter with Cassegrain optics in near future. System noise temperature of current MARBLE1 antenna is 200-300 Kelvins.

Both of two small antennas are capable of only single linear (Vertical) polarization observation. Current SEFD of MARBLE1 and MARBLE2 are $1 \sim 2 \times 10^6$ Jansky, and $2 \sim 4 \times 10^5$ Jansky, respectively in 3-11 GHz frequency range.

2.2 Data Acquisition and Signal Processing

Another new technology introduced in this project is "RF-Direct-Sampling" technique[7], which converts radio frequency analog signal to digital data by using high speed sampler K6/GALAS[8] at 16,384 MHz sampling rate without analog frequency conversion. Four bands of signals with 1 GHz bandwidth can be flexibly specified in 0 - 16 GHz frequency range, and they are extracted by digital signal processing. Then the data is acquired to high speed recording system through 10G-Ethernet interface. This RF-Direct-Sampling technique has an essential advantage at stable phase relation between the signals of each bands. Since precise group delay observable is obtained by linear phase gradient over broad frequency range, phase distortion caused by the signal transmission line from the radio telescope to the recording system has to be calibrated. Linear phase characteristics is the key feature to measure precision group delay with broadband signal. In case of analog frequency conversion, it is inevitable that unpredictable phase offset originated from local oscillator is added in that process. Conventionally, phase calibration signal (Pcal)[9] has been used to calibrate phase characteristics of the system including the offset and signal transmission path, however special care is needed to keep phase stability of the Pcal device itself. Because the timing of Pcal signal is triggered by reference signal, thus its phase can be changed by thermal extension of reference signal transmission cable. For monitoring and calibration of this change, Delay calibration system (Dcal) has been used at geodetic VLBI stations. Whereas in case of RF-Direct-Sampling,

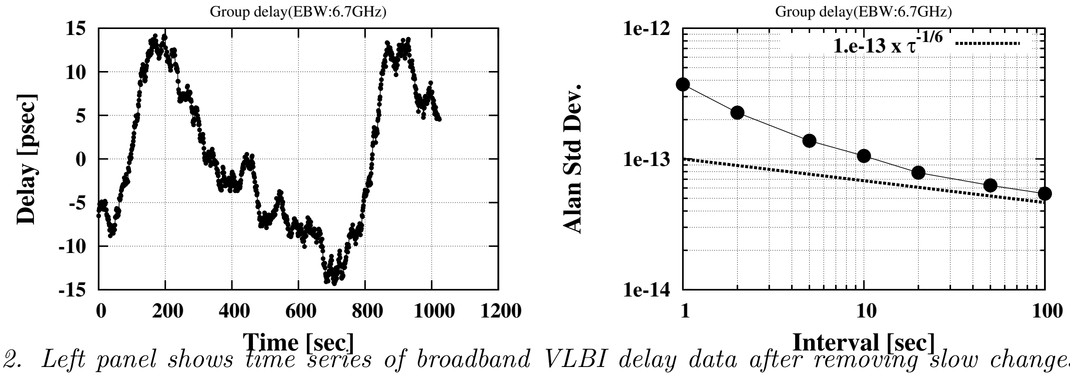

Figure 2. Left panel shows time series of broadband VLBI delay data after removing slow changes of delay for 3C273B on Kashima 34m - Ishioka 13m baseline. Every point represents delay data obtained by 1 second of integration by synthesizing four frequency bands. The random walk like delay behavior in the panel, which changes about 20 ps in a few hundred seconds, might be caused by atmospheric delay fluctuation. Right panel is Alan standard deviation computed from the delay data in the left panel. Dashed line indicates $\sigma(\tau) = 1 \times 10^{-13}\tau^{-1/6}$, which is an example of fluctuation evaluated by Kolmogorov turbulence theory and coefficient in literatures[12, 13].

phase relation among the four bands of signal is frozen at the point of digitization. Even though there are some amount of phase offset among the signals of each band due to difference of sampling timing of A/D devices and digital signal processing, they are quite stable.

To obtain linear phase characteristics over the wide spreading frequency bands, we used observed radio source signal for calibration of phase offset between bands. Radio sources with strong flux are observed a few times in a session, then one of the scans with high SNR is chosen as template for calibration. The cross correlation phase spectrum of the template scan data is applied to all the scans of whole session to calibrate the phase characteristics of signal transmission path and data acquisition. This method has been proven to work well in our broadband VLBI sessions.

The VGOS specification requires dual linear polarization observation, though only single linear polarization signal has been recorded in these domestic experiments. Because difference of paratactic angles are negligible on these short baselines.

Cross correlation of the data has been processed by using high speed software correlator GICO3 [10], which had been developed by NICT for astronomical broad band observation. Correlation output of four band of signals are synthesized by new wideband bandwidth synthesis (BWS) software 'komb'[11]. The BWS produces sharp peak in time domain after phase characteristic calibration by using template scan as described above. Fig. 2 shows a delay data of radio source 3C273B obtained by a test experiment on Kashima 34m - Ishioka 13m baseline in 2015. The data shows that sub-pico second delay precision was achieved by 1 second of observation. It is demonstrating potential of extremely high delay precision of the broadband observation system. The random walk like that delay behavior, which changes about 20 ps in a few hundred seconds, is thought to be caused by property atmospheric delay change. Alan standard deviation of the data shows consistent trend with an example of fluctuation (dashed line in the right panel of Fig.2) evaluated by Kolmogorov turbulence theory and coefficient in literatures [12, 13].

3. Broadband VLBI Sessions in 2016

Basic observation mode of the GALA-V system was allocating four 1024 MHz width data acquisition bands in 3-14 GHz frequency range with non-redundancy interval. Frequency allocation of band center at 4.0 GHz, 5.6 GHz, 10.4 GHz, and 13.6 GHz was the original plan. Although by taking into account practical condition such as radio frequency interference (RFI) and sensitivity of current receivers, slightly narrow frequency allocation at 5.9, 7.1, 8.7, and 10.6 GHz was used in the VLBI sessions in 2016.

Eight broadband VLBI sessions have been conducted during period between January to September 2016 (Table 1). Because the target of the project is frequency comparison of atomic standards, then session lengths are longer than 24 hours to get clock behavior in long time span. Extracted observation data of broadband VLBI sessions are stored to MK3 database and analyzed by Calc Ver.11.01 and SOLVE Release 2014.2.21 developed by NASA/GSFC(`http://gemini.gsfc.nasa.gov/solve/`). Estimation parameters in

Table 1. Broadband VLBI sessions during Jan.-Sep. in 2016. Kas34:Kashima 34m antenna, MBL1: MARBLE1 antenna, MBL2: MARBLE2 antenna, Ish13: Ishioka 13m antenna.

Date in 2016	Stations	Num. Scans Used/Recorded	Session Duration	Avg. Scan length
26-27 Jan.	Kas34 − MBL1 − MBL2	1330/1500	46 h	110 sec.
12-13 Feb.	Kas34 − MBL1 − MBL2	1250/1600	47 h	106 sec.
28-29 Feb.	Kas34 − MBL1 − MBL2	1050/1450	49 h	122 sec.
16-17 May.	Kas34 − MBL1 − MBL2	1220/1410	31 h	79 sec.
24-25 Jun.	Kas34 − MBL1 − MBL2	1800/1850	49 h	95 sec.
10-11 Jul.	Kas34 − MBL1 − MBL2	1960/2003	48 h	86 sec.
23-24 Aug.	Ish13 − MBL2	1372/1385	43 h	112 sec.
12-13 Sep.	Ish13 − MBL1 − MBL2	1600/1640	35 h	77 sec.

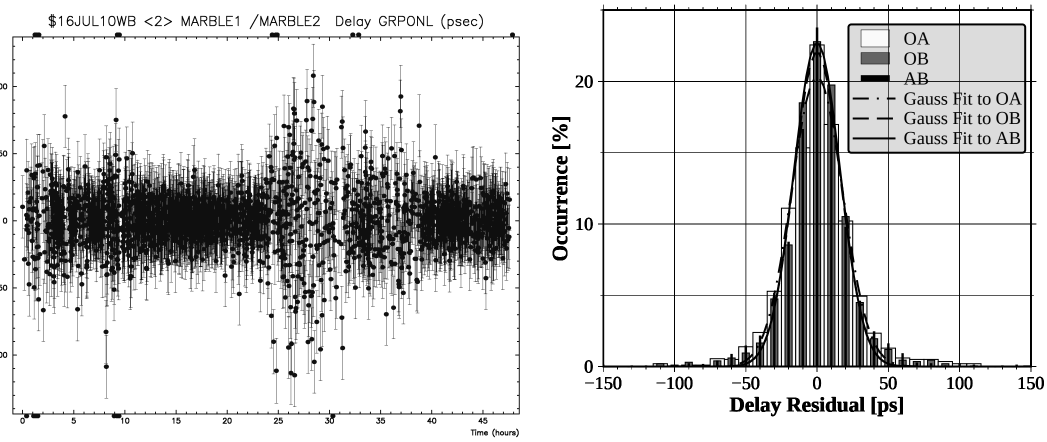

Figure 3. Post-fit delay residual of AB baseline in the session of 10-11 July, where delay of AB baseline was computed by linear combination of OA, and OB baselines. (O:Kashima34, A: MARBLE1, and B:MABLR2). Delay errors evaluated from SNR of BWS results was 4 ps or below for all the scans of AB baseline. Extra noise of 23 ps was added in the reweighting procedure to make reduced χ^2 unity.

VLBI analysis are station coordinates (XYZ), atmospheric delay with Niell's Mapping Function with 20 min. interval, and clock parameters in 60 min. interval. Since there is no ambiguity in our delay observable due to broad bandwidth, analysis procedure is simply flagging bad data and reweighting of data to make reduced kai-square unity. Delay residual of small antenna pair AB baselines in the session of 10-11 July is indicated in Fig.3.

As described at introduction, correlation processing for AB baseline is not performed, but the delay data of AB baseline is computed by linear combination of delays of OA, OB baselines with equation (1). Then delay error magnitude of AB baseline is supposed to increase as root sum square of the error of OA and OB baseline via error propagation law. However, post fit delay residual of AB baseline does not increase as expected. This indicates the post fit residual is dominated by extra error added to make reduced-kai-square to unity, which is added in the baseline analysis and it represents error due to un-modeled delay. This suggesting that degradation of delay error by linear combination process was negligible in these broadband sessions. A series of MARBLE2 station coordinates estimated with AB baseline data of broadband sessions are displayed in Fig. 4. By taking into account a linear trend of -10.5 mm/yr in E-W direction, repeatability of horizontal coordinates was about several milli-meters, and that of vertical coordinates was a few centimeters. Estimated 'Clock+residual' as the product of VLBI is plotted in Fig. 5. Their clock behavior is consistent with GPS ppp-solutions, though variation around the trend is larger on VLBI. Further improvement need to be investigated.

4. Summary

Broadband VLBI system GALA-V acquiring four 1 GHz band width in 3-14 GHz frequency range has now been ready for single linear polarization observation. Original designed broadband feeds has been developed to satisfy the conditions

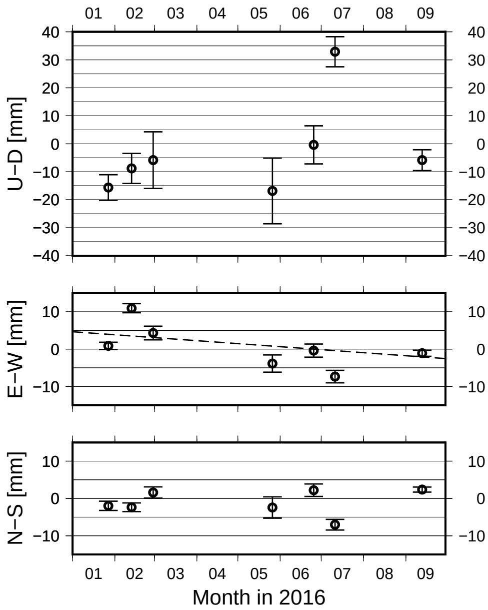

Figure 4. Series of MARBLE2 station coordinates estimated with AB baseline data are displayed for UP-Down, East-West, and North-South coordinates. Error bars of each point indicates formal error of the coordinates in each session. A linear trend of -10.5 mm/yr was observed in East-West direction, which we suppose to be due to local effect of the site. By taking into account removing this trend only in East-West coordinates, repeatability of the MARBLE2 station coordinates w.r.t the MARBLE1 coordinates are several milli-meters in horizontal and about a few centi-meters in vertical coordinates.

of broadband receiving and narrow beam width for Cassegrain focus. A new technique RF-Direct-Sampling by using K6/GALAS sampler demonstrated simplified data acquisition system without Pcal device. This system is working effectively for stable broadband delay measurement. Broadband bandwidth synthesis software was developed and it resulted ever achieved sub-pico second group delay measurement by broadband VLBI experiment. A series of broadband domestic VLBI sessions with GALA-V system have been conducted. VLBI delay data on the baseline of small diameter antenna pair were computed by linear combination of delay data with respect to larger antenna, and it was analyzed by CALC/SOLVE system. Repeatability accuracy of the geodetic solution of small antenna pair was several millimeters and a few centimeters in horizontal and in vertical coordinates, respectively. Atomic clock difference estimated a by VLBI observation between small diameter antenna

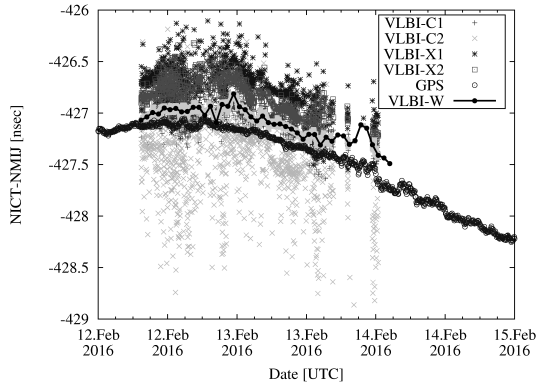

Figure 5. An example of 'Clock+residual' estimated by VLBI data in Feb. 12-14 session is plotted. Marks of ('+', 'x', '','□') are solution of single 1 GHz band of 5.9 GHz, 7.1 GHz, 8.7 GHz, and 10.6 GHz. The solid line and closed circle is broadband delay by synthesis of all bands. GPS analysis results is plotted with open circles. Vertical position of the VLBI data is shifted appropriately for comparison.*

pair has been successfully estimated. It shows consistent results with that measured by GPS observation.

Dual linear polarization observation will be indispensable in intercontinental broadband VLBI observation. Source structure effect may have to be considered in long baselines. We need development of data processing scheme of mixed polarization data, and further improvement of precision is subject for the next step.

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