An Overview of the Japanese GALA-V Wideband VLBI System

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Abstract NICT is developing a new broadband VLBI system, named GALA-V with aim of frequency comparison between atomic time standards over inter-continental baseline. The development of broadband GALA-V system is coordinated to be as compatible as possible with the VGOS system. Two types of original broadband feed systems were developed for Kashima 34m antenna of modified Cassegrain optics. The first prototype feed named IGUANA-H works at 6.5 - 16 GHz frequency range and the second feed NINJA works at 3.2 - 14 GHz range. The GALA-V observation system is designed to capture four bands of 1024 MHz width signal in 3 - 14 GHz range. Two sorts of data acquisition modes are available. One is narrow channel mode, which acquires multiple channels of 32 MHz width signals. This mode is compatible with the NASA proof of Concept (PoC) system developed by MIT Haystack Observatory. The other is broad channel acquisition mode, in which signal of 1024 MHz width is digitized as a single channel. Radio frequency (RF) direct sampling technique was used in this mode as a new approach for broadband observation with taking advantages of high speed sampler K6/GALAS and its digital filtering function. This technique has several advantages in precise delay measurement by broadband bandwidth synthesis. VLBI Experiments were conducted between Kashima 34m antenna and Ishioka 13m VGOS station of GSI of Japan. The first broadband observation over 8 GHz bandwidth was successful on this baseline in early 2015. Result of the broadband bandwidth synthesis over 8GHz bandwidth proved sub-pico second resolution group delay measurement in 1 second of integration. Time series of the group delay data shows several pico seconds of fluctuation in a few hundred seconds of time scale. That Alan standard deviation is consistent with frozen flow model of Kolmogorov tropospheric turbulence.

Keywords Broadband VLBI

1 Introduction

Time interval of SI second as timescale is defined by counting the microwave emission from Cs atom at 9,192,631,770 Hz. By recent progress of technology in quantum physics and optics, more accurate frequency standards are being realized by using optical emission of atoms[1]. Re-definition of time scale has been discussed as subject of metrology[2]. NICT is in charge of keeping Japan Standard Time as a national institute, and is engaged in a research and developing of optical frequency standards. Confirmation of identity of frequency generated by independent optical atomic standards is an important subject for re-definition of SI second.

Currently two-way satellite time and frequency transfer (TWSTFT) and observation of GNSS satellites are operationally used for distant frequency transfer. Advanced TWSTFT technology with carrier-phase [3] might provide enough precision over inter-continental distances, but it depends on availability of satellite transponders. VLBI has a potential enabling distant frequency transfer, and has been investigated by

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several studies [4]-[9]. One of advantages of VLBI is independence from availability of satellites. Development of more precise VLBI observation technology is in progress, and it is expected to advances VLBI application in geodesy and metrology.

The IVS is promoting deployment of VGOS as the new generation geodetic VLBI system. The VGOS system is characterized by high temporal resolution of observation by using fast slew antenna and broad radio frequency bandwidth. The fast slew observation is necessary for VGOS to improve correct atmospheric delay modeling and temporal resolution. VLBI group of NICT is developing a broadband VLBI system named GALA-V for application of VLBI to distant frequency transfer. The GALA-V system is basically designed to use the compatible radio observation frequency range and data acquisition system with the VGOS. Concept of the GALA-V system and development of original feed and data acquisition systems are described in the following section 2. Domestic broadband VLBI experiment between Kashima 34m and Ishioka 13m VGOS station was conducted in 2015. Observation condition and derived broadband delay is discussed in section 3. Finally, overall progresses are summarized in section 4.

2 Broadband VLBI System:GALA-V

2.1 Distant Clock Comparison with Small Antenna

Frequency comparison with VLBI is made by clock parameter estimation just as the same analysis with geodesy. Standard signal from atomic frequency standard are used as reference of VLBI observation at each station, thus VLBI delay observable on that baseline contains the difference between those atomic clocks. To utilize VLBI for atomic frequency transfer, VLBI station need to be located near the atomic frequency standard, except for the case that reference signal is delivered from remote atomic clock by stable fiber-link (e.g. [10]). Thus our GALA-V system uses transportable small VLBI stations as the terminal of comparison. Fig.1 schematically shows the concept of GALA-V broadband VLBI system. The GALA-V observation system is characterized by following techniques

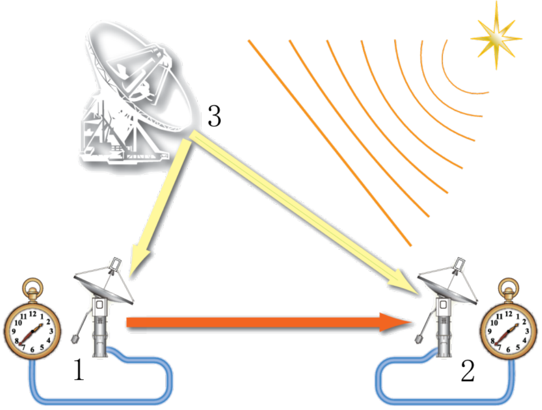

Fig. 1 Concept of GALA-V broadband VLBI system is schematically displayed.

1. High speed sampling: 1 GHz × 4 bands, 8 Gbps/polarization
2. Combination use of small antennas and large diameter antenna
3. Non redundancy array of observation frequency allocation to get fine delay resolution function.
4. Broadband observation :3 - 14 GHz
5. RF Direct sampling without frequency conversion.

Disadvantage of sensitivity of the small correcting area is recovered by using (1) broadband observation and (2) combination observation with large diameter antenna. Data acquisition rate of GALA-V system is 8192 Mbps corresponding 4 × 1 GHz bands, whereas conventional geodetic VLBI observation uses about 256 Mbps. It will bring about 5.6 ($=\sqrt{8192/256}$) times improvement of SNR than conventional VLBI. Signal to noise ratio of VLBI observation is expressed by products of system equivalent flux density (SEFD) of two stations as

$$SNR = \frac{S}{SEFD_1 \cdot SEFD_2}\sqrt{2Bt}, \tag{1}$$

where S is flux of radio source, B is observation bandwidth, and t is integration time. Thus even if SNR of VLBI observation with small antenna pair '1'-'2' is not sufficient to get enough SNR, joint observation with large diameter (boost) antenna '3' enables the interferometer to work. Delay observable of baseline $\tau_{21}(t_1)$ is computed by combination of two observable τ_{13} and τ_{23} by using closure delay relation as follows:

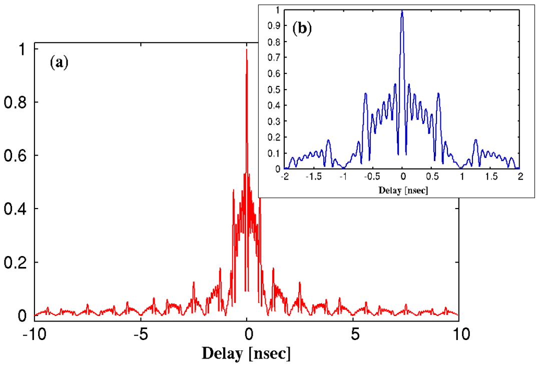

Fig. 2 (a)Delay resolution function expected from frequency array 4.0 GHz, 5.6 GHz, 10.4GHz, and 13.6GHz with 1 GHz bandwidth and (b) shows magnified plot around the center.

$$\tau_{21}(t_1) = \tau_{23}(t_3) - \tau_{13}(t_3) - \tau_{13} \times \dot{\tau}_{21} + \frac{1}{2}\tau_{13}^2 \times \ddot{\tau}_{21} + o_3, \quad (2)$$

when radio source structure effect is negligible. Though error of observable τ_{12} increases by root-square sum of error τ_{23} and τ_{13}, advantage of this method is that systematic error caused from boost station will be canceled out. Radio source structure effect in broadband observation is to be a subject of investigation.

After a local survey of radio interference environment, we have selected nominal frequency array of GALA-V system as 4.0 GHz, 5.6 GHz, 10.4 GHz, and 13.6 GHz as the center frequencies of observation band to be located. By allocating the array in non-redundancy interval, the delay resolution function has fine peak and low side-lobes as indicated in Fig.2

’RF Direct Sampling’ is our original approach to enable easy broadband phase calibration by observation of radio source. Stable phase relation between observing bands is remarkable characteristic of this method. More detail of this technique is described in latter section 2.3.

As well known, dominating error source of space geodetic techniques including VLBI is atmospheric delay, then fast switching essential to improve precision of both geodetic results and distant clock comparison. Therefore, the GALA-V project expects to make joint VLBI observation with VGOS station as boost station to improve both SNR and temporal resolution.

2.2 Broadband Feed Development

GALA-V system is designed to have common radio observation frequency range with VGOS for joint observation. Most of the VGOS stations uses Eleven Feed[11] or Quad ridged Flared Horn (QRFH)[12] to receive broadband radio signal. These feeds have broader beam size around 90 – 120 deg. Therefore all of VGOS antennas are newly built with special optics called “ring focus” design to adapt to the broad beam size.

As a different approach, we developed original broadband feed with narrow beam size (34 deg.) for Cassegrain optics of Kashima 34m antenna. The first prototype feed named IGUANA-H was produced in 2014. That is designed based on multi-mode wave composition, and it works at frequency range 6.5-16 GHz. The second prototype NINJA feed has been mounted on the 34m antenna in 2015, and it has sensitivity in frequency range 3.2 – 14 GHz.

Picture of Fig. 3(a) shows broadband receiver system of Kashima 34m antenna. The left hand side of the picture is NINJA feed, and right hand side is IGUANA-H feed. Frequency dependence of SEFDs of each feeds are indicated in Fig. 3(b) and (c).

2.3 RF Direct Sampling with K6/GALAS(OCTAD-G)

Current Standard VGOS observation system is based on the Proof of Concept (PoC) VLBI system developed in MIT/Haystack Observatory[13, 14]. This system uses UpDown converter (UDC) for selecting four bands of 1 GHz bandwidth from 2-14 GHz bandwidth. The signals converted to intermediate frequency (IF) are acquired by 32 channels of 32 MHz bandwidth with digital baseband conversion (DBBC, e.g. [15]–[17]) for each bands. The phase relation among the 32 video channels must be stable, because each video frequency channels are separated by digital signal processing after IF signal is converted to digital data. Although phase relations between four bands selected by using UDC are not always constant, but it may change and even be sensitive to temperature mainly because of the analog mixing components and local oscillators for each bands. The concept of VGOS is targeting to

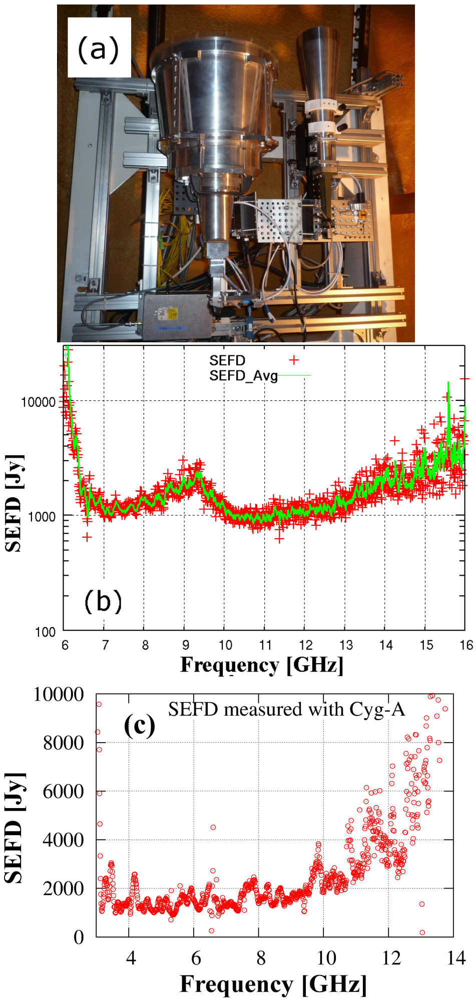

Fig. 3 (a) Picture of NINJA feed (left) and IGUANA-H feed (right). (b) SEFDs of IGUANA-H and (c) that of NINJA feeds.

derive so called 'broadband delay'[18] obtained by coherent synthesis of fringe phase over the four bands. Phase calibration signal, which is injected in the signal path from front end up to digital recording, is essential for calibration of the phase variation.

Our GALA-V system takes different approach: sampling the radio frequency (RF) signal without analog frequency conversion, which is named 'RF Direct Sampling' technique [19]. This technique was enabled by 16 GHz high speed sampler K6/GALAS(OCTAD-G). Outlook of this sampler is displayed in Fig. 4(a). National Astronomical Observatory of Japan (NAOJ) and Elecs Co Ltd have been developing a series of VLBI observation system named OCTAVE family [20]. High speed sampler OCTAD is a member of the OCTAVE family with 3-bit quantization at 8192 MHz sampling rate. The K6/GALAS is upgraded version of the OCTAD, and this sampler makes analog-digital (A/D) conversion at 16,384 MHz sampling rate with 3-bit quantization. Then digital filtering via internal FPGA is applied to extract 1024 MHz bandwidth signal at requested frequency. Nominal observing mode is 2048Msps-1bit-4band, then observed data come out at 8,192 Mbps data rate through 10GBASE-SR port with VDIF/VTP protocol over UDP/IP data stream.

Table 1 K6/GALAS Sampler specification parameters.

Input	
Number of inputs	2
Input Freq. Range	0.1-16.4 GHz
Sampring Rate	16,384 MHz or 12,800 MHz
Quantization Bit	3 bit
Output	
Sampling Mode	Broadband Mode 3200 Msps :1,2 bit 6400 Msps : 1,2 bit 12800 Msps: 1 bit
	DBBC Mode Lo resolution of frequency is 1MHz. Nch: 1,2,3,4 Sample rate: 2048 Msps Quantization bit: 1 or 2bit
Max data rate/sampler	16384 Mbps
Output Interface port	10GBASE-SR (SFP+) , 4 ports
Data format	VDIF/VTP over UDP/IP
Control	telnet /1000BaseT

Block diagram of signal input to the sampler is indicated in Fig. 4(b). Power divider and anti-aliasing filters have to be used to eliminate folding of signal at 8,192 MHz. Then signal is fed to two RF input ports to obtain four 1024-MHz bands allocated over 3-14GHz frequency range. Since the dynamic range of A/D conversion at the input is limited, input power level need to be equalized over the broad frequency range. Data acquisition parameters and interface specifications of K6/GALAS sampler are indicated in Table 1.

2.4 *Wideband Bandwidth Synthesis without Pcal Signal*

Remarkable advantage of the 'RF Direct Sampling' is its stable phase relation that enables broadband band-

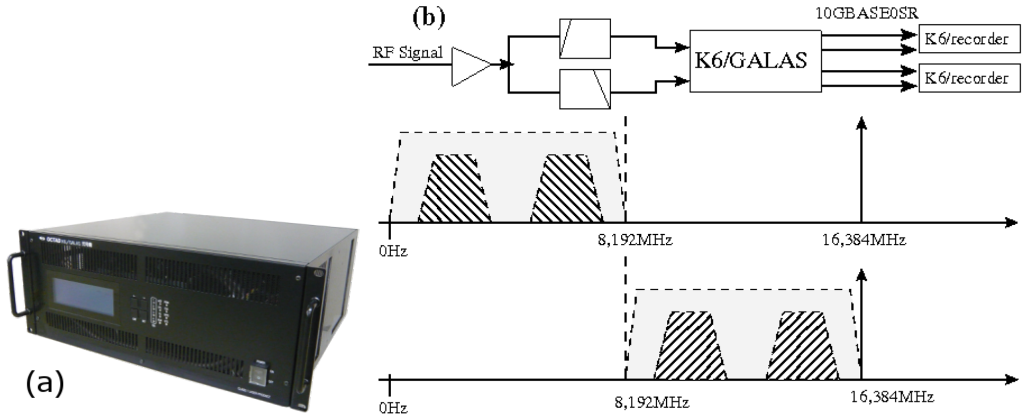

Fig. 4 Outlook of the K6/Galas sampler is displayed in panel (a). (b) Block diagram from sampler input to data recording. Two anti-alias filters are used for elimination of folding of signal by sampling rate at 16,384 MHz.

width synthesis without phase calibration signal (Pcal). The phase calibration technique with Pcal signal has been used since 1980s[21] to utilize the invention of bandwidth synthesis[22]. The most significant phase change in the signal chain of the observation system happens at the frequency conversion. It is unavoidable that local oscillator's initial phase is included in the converted signal. Consequently, large phase differences between signals happen naturally. The Pcal signal has been effectively corrected phase differences in the signal chain of multi-channel VLBI systems (e.g. [21],[23]). Frequency range to be synthesized has been up to 1 GHz width in the conventional VLBI system, whereas in VGOS and GALA-V system cases bandwidth to be synthesized is about 10 times wider than conventional VLBI. Broadband phase calibration is the essential technology to achieve such high delay resolution, thus broadband Pcal signal have to be quite stable.

The 'RF Direct Sampling' technique enables broadband phase calibration without Pcal signal. Observed signal is converted to digital data at radio frequency region without frequency conversion, then the phase relation of the signal is conserved at this point. Required frequency bands are extracted by digital signal processing, after that, Since frequency conversion is major cause to insert phase difference between bands, we can expect phase relation over the captured broad frequency range will be stable enough to eliminate calibration with Pcal signal.

Wideband bandwidth synthesis algorithm (WBWS) [24] is being developed, in which bandpass cross spectrum phase obtained with strong radio source is used to broadband phase calibration. The WBWS estimates ionospheric dispersive delay and broadband group delay simultaneously. Instead of using Pcal signal, this WBWS method requires 'calibration scan' (CalScan) within a VLBI session. The CalScan is an observation of compact strong radio source with relatively long duration to get sufficiently small phase error in cross correlation spectrum. Since the CalScan cross correlation phase data contains not only instrumental delay, but also geometrical delay, ionospheric delay, and atmospheric propagation delays of the scan, user have to be aware that the group delay obtained by the WBWS is a differential delay with respect to the CalScan.

3 Broadband VLBI Experiment and Delay Variation

3.1 Kashima - Ishioka Experiment

Geospatial Information Authority of Japan (GSI) has constructed a new 13.2 m diameter VLBI station[25] at Ishioka city in Japan. The Ishioka station is fully compliant of VGOS specification, thus Kashima 34m of NICT and Ishioka 13m of GSI are only two stations in Japan with broadband receiver system with better SEFD than 2000 Jy. In collaboration with GSI, we have installed K6/GALAS DAS at Ishioka station in August 2015. A test VLBI experiment with observation frequency range in 3.2 - 12.6 GHz was conducted on this baseline. Observation parameters of this experiment is indicated in Table 2.

Table 2 Observation parameters of Broadband VLBI experiment in Aug. 2015 on Kashima 34m - Ishioka 13m baseline.

Date and Duration	2015y226d06h40m – 227d14h59m (32h20m),
Scan	2 scans of 1200 sec. and 1188 scans of 30 sec.
Frequency Array [MHz]	3200-4224, 4600-5624, 8800-9824, 11600-12624
Effective bandwidth	3.3GHz
Data Acquisition	K6/GALAS & K6/recorder
Data Acquisition Mode	2048Msps-1bit-4band
Polarization	Vertical - Vertical

Only one linear polarization was available with NINJA feed of Kashima 34m station at this time. And the baseline between Ishioka 13m and Kashima 34m station was very short (48.6km), thus parallactic angle of the polarization is negligible. Then observation was made with one vertical linear polarization at both stations. The experiment included a long scan (1200 sec.) and short scan (30 sec.) for more than 24 hours. The purposes of long scan were two folds: for examining broadband delay behavior in this experiment and for obtaining CalScan data for WBWS processing. Cross correlation processing was done by software correlator GICO3[26] for each band. Then post correlation data were processed with upgraded bandwidth synthesis software 'komb'(Ver.2015-4-27) [24].

The process of WBWS include estimation of dispersive delay and broadband group delay. Cross spectrum phase is modeled by

$$\phi_{\mathrm{meas}}(f) = \alpha \frac{\delta TEC}{f^2} + \delta\tau_{\mathrm{a}} + \phi_o, \qquad (3)$$

where the first term in right hand side is dispersive delay corresponding to difference of total electron content (δTEC) in lines of sight from each observation station, and the second term is non-dispersive delay including geometrical delay and tropospheric delay. Fig. 5 (a) shows cross spectrum phase, and panel (b) shows time series of estimated δTEC. Let me remind reader that these data are differential quantities with respect to that of CalScan used in the process. It is notable that up to seveal TECU [1] of dispersive delay contribution exist even in short 48.6 km baseline.

3.2 Broaband Delay

Fig. 6 (a) shows a time series of group delay data of 1 second integration after removal of 2nd order of slow delay change by polynomial fitting, and its Alan standard deviation (ASD) is displayed in panel (b). That scan was about 1000-second-long for 3C273B. The plot of ASD indicates that the broadband delay of this case (effective bandwidth 3.3 GHz) reaches to sub-pico-second precision at 1 second observation when strong radio source is observed.

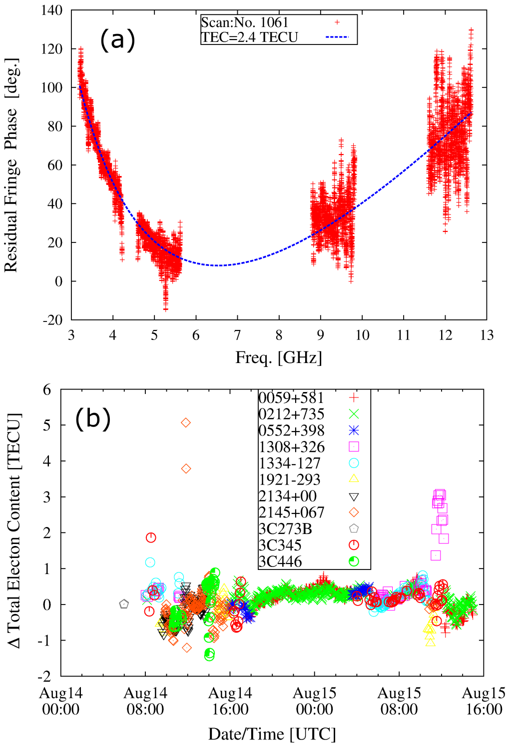

Fig. 5 (a) An example of cross correlation phase spectrum. Dashed line is plot of eqn.(4) with parameter fitted to the data. (b) Time series of estimated δ TEC obtained in the experiment. Each symbols corresponds to each radio sources.

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[1] 1 TECU = 10^{16} electrons/m^2

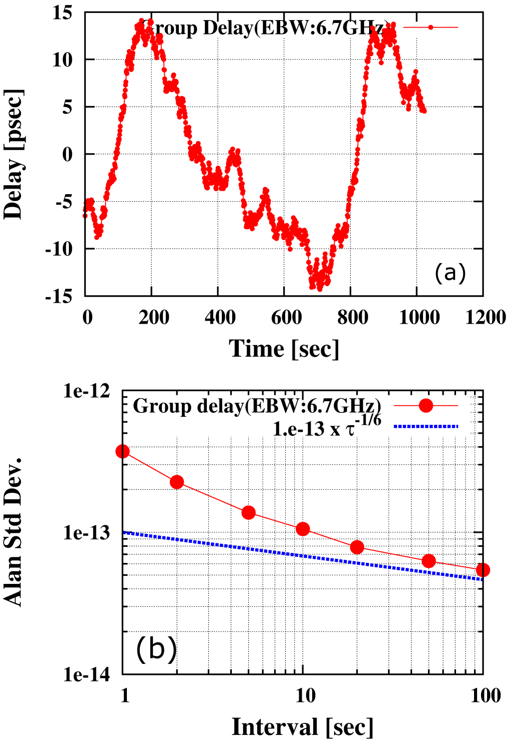

Fig. 6 (a)Time series of group delay data of derived by WBWS after removal of 2nd order of slow delay change, and (b) Alan standard deviation of the delay data. Dashed line in panel (b) indicates $\sigma_y = 10^{-13}\tau^{-1/6}$.

It is notable that group delay change in order of 10 pico seconds magnitude in hundreds seconds of time scale was observed with very high precision. There are several candidates of causes which can affect to group delay variation: troposphere propagation excess delay, instrumental delay, radio source structure effect, ionospheric delay, and model error of geometrical delay. Model error of geometrical delay will cause slow variation related with earth rotation. Also, radio source structure effect will change the group delay by rotation of projected baseline with respect to the source. Thus these two are unlikely to be reason of this short time variation. Rapid change of ionospheric delay may be caused by traveling ionospheric disturbances (TID, eg.[27]), which is 100 km scale with order of 1 TECU amplitude traveling with velocity around 400 km/hour. Its time scale is about 1000 sec., then it seems to be tool long to explain this variation. Tropospheric delay is known as dominating error source of space geodetic observations. Alan variance of tropospheric delay in interferometric observation is modeled by frozen flow of Kolmogorov turbulence[28].

$$\sigma_y^2(\tau) = 1.3\times10^{-17} C_n^2 L v_s^{5/3} \tau^{-1/3}, \qquad (4)$$

where $C_n^2 L$ is constant of turbulence, v_s is wind velocity on ground surface in m/s, and τ is time interval. Armstrong and Sramek[29] has measured $C_n^2 L$ as $2\times10^{-13} \sim 2\times10^{-9}$ for 35 km spatial scale. By using wind speed (4 m/s) measured on the ground at the time of observation, ASD can be computed as $4.8\times10^{-13} \sim 2\times10^{-15}$ at $\tau = 1$ second interval. Fig. 6(b) shows the ASD derived from the time series of group delay and plot of $\sigma_y(\tau) = 10^{-13}\tau^{-1/6}$. This good agreement between measurement and model on slope and magnitude of ASD suggests that delay fluctuation may be attribute to tropospheric turbulence.

Baseline analysis was made with CALC/SOLVE[30] on this broadband VLBI experiment. Though delay precision is better than 1 pico sec. for each data point, root mean square (RMS) of the post fit delay residual after standard parameter estimation was 34 pico sec. with large Chai-square value. That means the scattering of the residual cannot be explained by the magnitude of delay error computed from the SNR and bandwidth. Re-weighting of the data with additive noise of 55 pico sec. makes Chai-square unity. This result suggesting that un-modeled error is dominating the error of VLBI analysis, and that will be tropospheric delay as suggested from delay fluctuation data. Formal error of station coordinates in final solution was 3-4 mm in horizontal and 1.3 mm in vertical direction.

4 Summary

NICT is developing a wideband VLBI system GALA-V for application of distant frequency transfer. The observing radio frequency range is compatible with VGOS specification. To enable broadband observation with Kashima 34m radio telescope of Cassegrain optics, two types of original broadband feeds named IGUANA-H (6.5-16 GHz) and NINJA(3.2-14 GHz) have been developed. A new high speed sampler K6/GALAS has been introduced for using ’RF Direct Sampling’ technique. The remarkable advantage of ’RF Direct Sampling’ is stable phase relation between the bands selected by digital filtering. Since signal path is simple and data is digitized in early stage, high stability on phase and path length of the signal can be anticipated. Broadband delay is derived by WBWS processing via phase calibration with radio source signal (CalScan).

We have conducted a broadband VLBI experiment between Kashima 34m antenna and Ishioka 13m station, which is the only one full-spec VGOS station in Japan build by GSI in 2014. The experiment was composed of geodetic session with 1188 scans of 30 sec. duration and two scans of long 1200 sec. duration. Cross correlation processing was made by using software correlator GICO3. Phase characteristic of post correlation data of whole bandwidth were calibrated with phase data of reference radio source (CalScan), then broadband group delay and dispersive δTEC were simultaneously estimated in WBWS process. The experiment has proven that the broadband delay enables sub-pico second precision group delay measurement in 1 sec. of integration. The behavior of delay observable shows a fluctuation, which is consistent with frozen flow model of Kolmogorov tropospheric turbulence.

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