Broadband VLBI System GALA-V and Its Application for Geodesy and Frequency Transfer

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Abstract We have developed new broadband VLBI system, which include broadband feed, data acquisition system, and data processing software to derive precise group delay observable. The system is intended to be compatible with the VGOS (VLBI Global Observing System) specification. A newly developed broadband NINJA feeds has been mounted at the Cassegrain focus of Kashima 34m antenna and two small diameter VLBI antennas. RF-Direct sampling (RDS) technique was introduced by using high speed sampler K6/GALAS(OCTAD-G). The RDS has great benefit not only simplification of the data acquisition system by eliminating analog frequency converter, but also increasing phase stability of the signal. This characteristic is essentially contributing to sub-pico second precision delay measurement achieved by wideband bandwidth synthesis. We conducted a series of broadband VLBI experiments between two small telescopes installed at NICT(Tokyo) and NMIJ(Tsukuba) for measurement of clock difference between UTC(NICT) and UTC(NMIJ). Those results demonstrated that broadband VLBI system enables pico-second precision observation even with small diameter radio telescopes.

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1 Introduction of the GALA-V Project

Concept of broadband VLBI system for the next generation geodetic VLBI system has been discussed by the IVS working group(Niell et al., 2006). And it has been realized as the VGOS (VLBI Global Observing System). Stimulated by the VGOS concept, we has started development of a broadband VLBI system named GALA-V for application to accurate frequency comparison on long baseline. We employed small diameter antennas (MARBLE1 and MARBLE2) as relocatable VLBI station. Standard signals generated by atomic clocks to be compared are used for frequency standards at each small VLBI stations, and they are compared by observation. Disadvantage of the small collecting area of the antenna is compensated by two techniques. One is expanding observation bandwidth. Signal to noise ratio (SNR) is proportional to square-root of the signal bandwidth, then increasing frequency width of signal channel from conventional 8 MHz to 1024 MHz gains $\sqrt{128} = 11$ times improvement. The second technique is joint VLBI observation with larger diameter antenna, because the sensitivity of VLBI observation is proportional to the product of diameter of antenna pair. Fig. 1 shows image of the GALA-V project and 34m and 2.4m diameter antennas used in the project. Once 'large-small' diameter antenna pair works as VLBI station, delay observable on 'small-small' diameter antenna pair can be computed by using closure relation from two of 'large-small' baseline data of the same epoch, where radio source structure effect

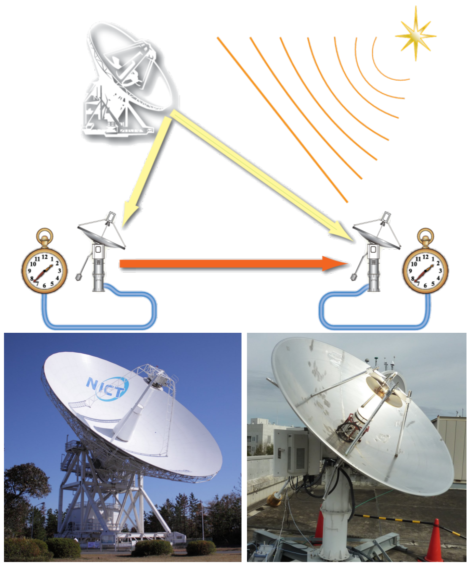

Fig. 1 Image of Gala-V project is illustrated in the figure above. Small antennas are used for tool for geodesy by joint observation with large diameter antenna. Kashima 34m (left) and 2.4m diameter Cassegrain antennas (right) are capable of super broad frequency (3-14 GHz) observation via new broadband NINJA feeds.

is supposed to be compensated or small enough to be eliminated.

This report describes topics of GALA-V system development.

2 Broadband Feed and Signal Chain

New VGOS telescopes are starting up in many countries, and almost all of new VGOS stations employes either Eleven Feed System(Yang, et al., 2011) or Quadruple-Ridged Flared Horn(Akgiray, et al., 2013) for the receiver. Since these feeds have wide opening angle around 120 degrees, ring focus optics have been chosen for new telescopes being built. However, in our case, Kashima 34m antenna's full viewing angle of sub-reflector from the focal point is fixed to be 34 degrees from geometry. Due to this reason, we have developed our own multi-mode feed named IGUNA-H(Ujihara, 2016) for 6.5-15 GHz frequency range as the first prototype. And second prototype NINJA feed for 3.2-14 GHz frequency range has been used at Kashima 34m and two small diameter telescopes in our project. Picture of the broadband feeds mounted at Kashima 34m antenna is displayed in Fig. 2. For quick development and for cost restriction, room temperature LNA has been used, then modified system temperature (Tsys$*$) is about 150-300 K for 3-14 GHz frequency range.

Fig. 2 Picture of broadband feed system of Kashima 34m antenna. NINJA feed in the left side and IGUANA-H feed in the right hand side.

Received signal is transmitted to observation room via broadband optical signal transmission system. Amplitude slope of the signal over the frequency is inevitably caused by insertion loss of any microwave components including frequency response of A/D converter, though this causes a significant signal loss at higher frequency. Thus, compensation of the amplitude slope by using passive equalization device is important in the signal chain.

3 RF-Direct Sampling and Phase Calibration with Radio Source

As it has already mentioned in the "Vision of VLBI2010"(Niell et al., 2006), RF-direct Sampling (RDS) technique has several advantages. Not only it enables simplified backend system, digitalization at early stage of signal chain brings benefit of stable phase relation of signal between channels. That is essentially important for precise group delay measurement. The block diagram of RDS and signal in frequency domain are illustrated in Fig. 3. Observed radio frequency signal is converted to digital data by using highspeed sampler K6/GALAS. Extraction of four channels of 1024 MHz width are made by FPGA digital signal processing implemented in the sampler. Frequency allocation within the input signal

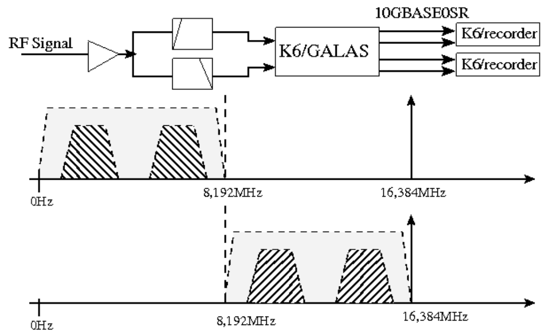

Fig. 3 Diagram of RF-Direct Sampling with 16GHz sampler K6/GALAS. Two RF inputs (DC-8 GHz and 8-16 GHz) are digitized, and four channels with 1 GHz frequency width are extracted by digital BBC function inside the sampler.

is selectable by 1 MHz resolution. Acquired data of each channel comes out by 2048 Msps in 1 bit or 2 bit quantized via VDIF/VTP/UDP data stream through 10GBASE-SR interfaces. We have been routinely using off-the-shelf computer with 10GBASE-SR NIC and RAID disk system for recording of 8192 Mbps data stream.

Conventionally, phase calibration (Pcal) signal has been used to recover linear phase response of the entire VLBI observation system for precise group delay measurement. The target of phase correction via Pcal signal is extra phase added at stage of frequency conversion and phase delay in the signal transmission path. It is unavoidable that unknown initial phase of local oscillator is inserted in analog frequency conversion. In case of RDS data acquisition, phase relation between channels are frozen at digitization, and further filtering and frequency conversion are made by digital signal processing. Then causes of phase variation are limited such as small change of signal transmission path length and change of sampling timing. Therefore, conventional Pcal signal is less important in RDS data acquisition.

Even though the RDS technique is used, linear phase relation is not always preserved in raw data, because physical signal path to two A/D converters and delay steps in digital signal processing might be slightly different between channels. Hence, we introduce phase calibration by using natural radio source to recover linear phase relation. When cross correlation phase at frequency ω is given by $Cor(\omega) = A(\omega)\exp\{j\phi(\omega)\}$, phase $\phi(\omega)$ includes several components as follows:

$$\phi(\omega) = \phi_{\rm geom} + \Delta\phi_{\rm atm} + \Delta\phi_{\omega,\rm ion} + \Delta\phi_{\omega,\rm feed} + \Delta\phi_{\omega,\rm trans} + \Delta\phi_{\omega,\rm DAS} + \phi_{\omega,\rm src}, \qquad (1)$$

where Δ means difference between two radio telescopes. Suffix 'geom', 'atm', 'ion', ' feed', ' trans', ' DAS', and ' src' represents geometrical delay, neutral atmospheric propagation delay, ionospheric dispersive delay, frequency dependent feed characteristics, signal transmission path, data acquisition system, and radio source structure, respectively. Here we omit the source structure effect, since it is subject to be discussed separately.

Let us suppose, ideal radio source, which is located at identical celestial coordinates as a point source in all the observing bands. We observe such radio source as a reference scan with sufficient integration time for good SNR. Correlation phase of the 'reference scan' $\phi(\omega)_{\rm ref}$ is used for calibrate phase of ith scan $\phi(\omega)_{\rm i}$, where instrumental phase of $\Delta\phi_{\rm feed}$, $\Delta\phi_{\rm trans}$, and $\Delta\phi_{\rm DAS}$ are supposed to be constant over the time. Consequently, calibrated cross correlation phase contains differential ionospheric delay and constant group delay offset.

$$\begin{aligned}\Delta\phi_{\rm i} &= \phi(\omega)_{\rm i} - \phi(\omega)_{\rm ref} \\ &= \phi_{\rm geom,i} - \phi_{\rm geom,ref} + \Delta\phi_{\rm atm,i} - \Delta\phi_{\rm atm,ref} \\ &\quad + \Delta\phi_{\omega,\rm ion,i} - \Delta\phi_{\omega,\rm ion,ref} \\ &= \phi_{\rm geom,i} + \Delta\phi_{\omega,\rm atm,i} - \frac{\Delta TEC_{\rm i} - \Delta TEC_{\rm ref}}{\omega} \\ &\quad + A \times \omega \end{aligned} \qquad (2)$$

The constant A corresponds to group delay of geometry and neutral atmosphere of reference scan. Dispersive differential ionospheric contribution can be separately estimated and excluded by $1/\omega$ dependency of correlation phase. Finally, all the cause of non-linearity of phase originated from instrumental and data acquisition are eliminated and linear phase characteristic is recovered for broad frequency range. Only one drawback is including of group delay offset A, though it can be absorbed in clock offset.

It is reported that radio source structure effect become significant at projected baseline length get longer (e.g. Xu et al., 2016). This effect need to be investigated and to be taken into account for intercontinental baseline.

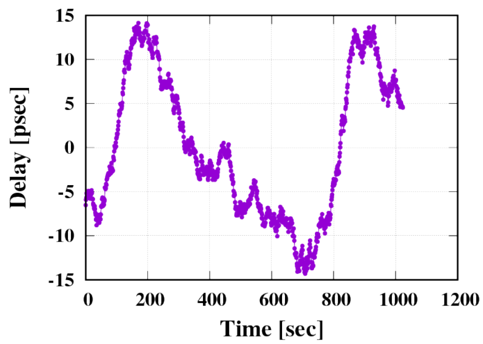

Fig. 4 Broadband delay observed on Kashima34 – Ishioka 13m baseline is plotted after removing slow delay change caused by geometrical delay. Each points are derived by broad bandwidth synthesis by 1 second integration. Delay measurement precision has been evaluated about 4.e-13 sec. at one second.

4 Broadband Group Delay and Comparison with Conventional Multi-channel Delay

Linear phase response over frequency range (3-12 GHz) can be realized, as described in the previous section. Based on this calibration technique, extremely precise group delay can be determined by coherently synthesizing broadband signal. This wideband bandwidth synthesis software has been developed by Kondo and Takefuji (2016). Hereafter we call the group delay obtained by synthesizing broadband cross correlation data as 'broadband-delay'. Fig. 4 shows an example of broadband-delay obtained between Kashima 34 m and Ishioka 13 m radio telescope with frequency array of 3.2, 4.8, 8.8, and 11.6 GHz. Each point in the plot is broadband-delay derived by one second integration. The data shows that the delay precision reaches to sub-pico second level by one second of integration. Additionally, random walk like delay change in the order of a few tens of pico seconds has been observed during hundreds seconds of timescale. Most probable cause of this delay behavior is propagation delay due to inhomogeneous water vapor in the atmosphere.

As described in section 1, delay observables between 'small-small' antenna pair are derived by closure delay relation. In 2016, a series of broadband VLBI experiments were conducted 10 times with two small VLBI antennas and 34m antenna (O). Two small antennas are 1.6 m diameter broadband antenna (MARBLE1:A) installed at National Metrology Institute of Japan (NMIJ) in Tsukuba and 2.4m diameter broadband antenna (MARBLE2:B) installed at headquarter of NICT in Tokyo. Frequency arrays of the GALA-V observation were not always the same for all of the ten sessions. Nominal frequency array of the GALA-V project is 3.5, 5.1, 9.9, and 13.1 GHz, which results in 3.8 GHz effective bandwidth (EBW). The minimum EBW is 1.78 GHz when frequency array was 5.9, 7.1, 8.7, and 10.6 GHz. Reference scans, which is used for correlation phase calibration, were included three times in every sessions with about 1200 sec. duration. These scans were used for evaluation of delay measurement precision. Time series of broadband-delays ($\tau_{\rm OA}, \tau_{\rm OB}$) have been derived with one sec. integration. Then, delay observables of 'small-small' baseline ($\tau_{\rm AB}$) were computed by linear combination of $\tau_{\rm OA}$ and $\tau_{\rm OB}$. These broadband-delay data are plotted in Fig. 5.

For comparison between broadband-delay and conventional multi-channel delay in X-band, observation in X-band with 2000 second duration was conducted with 11 m diameter antenna pair of Kashima - Koganei 100 km baseline. Roughly speaking, 2.4 m and 34 m diameter antenna pair has equivalent sensitivity with $\sqrt{2.4*34} = 9$ m antenna pair. VLBI observation of 3C273B with Kashima 11 m - Koganei 11 m baseline was made on 10 April 2017 with X-band frequency array: 8210.99, 8220.99, 8250.99, 8310.99, 8420.99, 8500.99, 8550.99, and 8570.99 MHz with each 8 MHz bandwidth. Effective bandwidth of this array is about 133 MHz. For sufficient SNR, nine second of integration time was chosen. Multi-channel delay after removing slow geometrical delay change is superimposed with open circle in Fig. 5. Since the typical rms residual of geodetic VLBI analysis of Kashima 11m - Koganei 11m baseline is around 30 pico sec., scattering of the multi-channel delay in this plot represents proper performance of the observation system. This plot tells us several findings. (1) Broadband delay is significantly higher precision than conventional multi-channel delay with X-band. (2) Broadband-delay shows random walk like delay change with a few tens of pico seconds of amplitude within hundred seconds of timescale. Potential cause of delay changes would be (a) change of electrical path from feed system to the sampler. (b) drift of sampling timing (c) excess delay change caused by signal propagation medium. We suspect most probable cause of this will be (c), which is attribute to small scale inhomogeneity of atmosphere. Contribution from other error source (a) and (b) should exist. However, 20

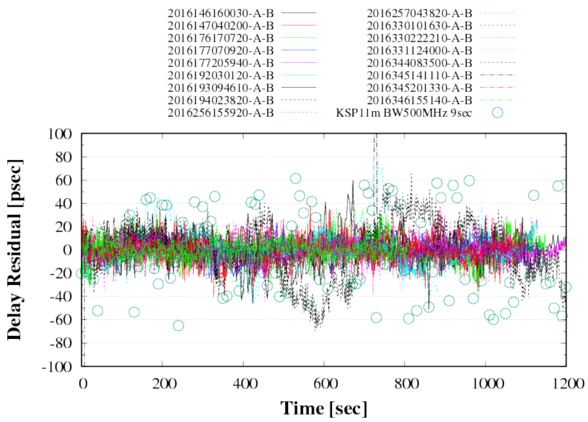

Fig. 5 Broadband-delay of MARBLE1-MARBLE2 baseline data observed in in 2016 are plotted with lines of each color. Slow geometrical delay changes are removed from these data in advance. Numbers of notations indicate time tag of the scan in yyyydddHHMMSS format. Broadband-delays were derived every one or four second intervals. Conventional multi-channel delays of Kashima 11m - Koganei 11m baseline was observed with 8 channels at X-band within 500 MHz width. These data are plotted by 9 sec. interval with open circles.

pico sec (=16mm) amplitude change within a few hundreds of seconds is too large, thus these are unlikely to be dominating error source.

5 Conclusions

We have developed new broadband VLBI system, which include broadband feed, data acquisition system, and data processing software to derive precise group delay observable. It was demonstrated that broadband-delay observable has potential to measure group delay in sub-pico second precision. Even small (1.6 - 2.4 m) diameter antenna pair can make precise group delay measurement by broadband observation and joint observation with large diameter antenna. The delay precision was superior to conventional multi-channel delay observation with 11m diameter antenna pair.

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References

A. Niell, A. Whitney, B. Petrachenko, W. Schlüter, N. Vandenberg, H. Hase, Y. Koyama, C. Ma, H. Schuh, G. Tuccari, *VLBI2010: Current and Future Requirement for Geodetic VLBI System*, International VLBI Service for Geodesy and Astrometry 2005 Annual Report, edited by D. Behrend and K. Baver, NASA/TP-2006-214136, pp. 13-40, 2006.

W.T. Petrachenko, A.E. Niell, B.E. Corey, D. Behrend, H. Schuh, J. Wresnik, *VLBI2010:Next Generation VLBI System for Geodesy and Astrometry*, In: S. Kenyon, M.C. Pacino, U. Marti (eds.), Geodesy for Planet Earth, International Association of Geodesy Symposia 136, Springer-Verlag Berlin Heidelberg, ISBN 978-3-642-20337-4, pp. 999–1006, 2012.

J. Yang, M. Pantaleev, P.-S. Kildal, B. Klein, Y. Karandikar, L. Helldner, N. Wadefalk, C. Beaudoin, Cryogenic 2–13 GHz Eleven Feed for Reflector Antennas in Future Wideband Radio Telescopes, *IEEE Trans. Antennas Propag.*, 59, 6, pp. 1918-1934, 2011.

A. Akgiray, S. Weinreb, W.A. Imbriale, and C. Beaudoin, Circular Quadruple-Ridged Flared Horn Achieving Near-Constant Beamwidth Over Multioctave Bandwidth: Design and Measurements, *IEEE Trans. Antennas Propag.*, 61, 3, pp. 1099–1108, 2013. doi: 10.1109/TAP.2012.2229953.

H. Ujihara, Development of wideband feed for Kashima 34 m Antenna,*Radio Sci.*, 52, 2016. doi: :10.1002/2016RS006071.

M.H. Xu, R. Heinkelmann, J.M. Anderson, J. Mora-Diaz, H. Schuh, G. L. Wang, The Source Structure of 0642+449 Detected from the CONT14 Observations, *AJ*, 152, 5, pp.11, 2016. doi: 10.3847/0004-6256/152/5/151.

T. Kondo, and K. Takefuji, An algorithm of wideband bandwidth synthesis for geodetic VLBI, *Radio Sci.*, 51, 2016. doi: 10.1002/2016RS006070.

T. Hobiger, T. Kondo, T. Koyama, MK3TOOLS & NetCDF - storing VLBI data in a machine independent array oriented data format, *Proc. of 18th European VLBI for Geodesy and Astrometry (EVGA) Working Meeting*, `http://www.evga.org/files/2007EVGA-proc_Vienna.pdf`, pp. 194 – 195, 2007.