Development of a Wideband VLBI System (GALA-V)

Mamoru Sekido, Kazuhiro Takefuji, Hideki Ujihara, Masanori Tsutsumi, Yuka Miyauchi, Shingo Hasegawa, Thomas Hobiger, Ryuichi Ichikawa, Yasuhiro Koyama

Abstract The VLBI group of the National Institute of Information and Communications Technology (NICT) has been developing a wideband VLBI observation system, which is semi-compliant with the VGOS system. Two small-diameter, transportable antennas and a 34-m antenna are prepared for wideband observations at the 3–14 GHz frequency range. This project, named "GALA-V", is intended to be used for precise frequency comparisons between widely separated atomic frequency standards. Several new challenges are being addressed in this project: (1) development of a wideband feed with narrow beam width for a large-diameter Cassegrain antenna, (2) development of a direct RF sampling data acquisition system, which samples the RF analog signal at 16 GHz. A prototype of the new wideband feed has been installed on the 34-m antenna at the end of 2013. The current status of this GALA-V project development is described in this report.

Keywords Broadband feed, direct sampling

1 Introduction

The unit of time, one second, which is currently defined by counting the microwave frequency emitted by a Cs atom, might be replaced by a new definition in which the second is realized by counting the optical frequency emission from some atoms (e.g., [1]). Such a development for a new atomic frequency standard is in progress in the field of quantum mechanics and metrology. NICT, as the Japanese Time Standard Authority, is in charge of keeping time and frequency, and it is developing new optical time standards too. Two-way satellite time and frequency transfer (TWSTFT) and GNSS observations have been used for frequency comparisons by domestic and international institutes [2]. Other space technologies, such as VLBI and SLR, are being investigated for T&F transfer applications [3, 4]. We are developing a VLBI system composed of a transportable, small-diameter antenna pair and a large-diameter antenna for distant frequency comparison. Two small-diameter antennas are to be placed at each site of atomic frequency standards, and their frequencies are compared via VLBI observations using those signals as the frequency reference at each station. We named this VLBI system (Project) "GALA-V". One of the small-diameter antennas and the 34-m diameter antenna as the component of the system are displayed in Figure 1. To compensate for the reduced sensitivity of the small-diameter antenna, two measures are taken to improve the system: (1) combi-

Fig. 1 A 1.5-m diameter antenna located at NICT headquarters in Koganei (left) and the 34-m diameter antenna at Kashima Space Technology Center (right).

National Institute of Information and Communications Technology, Kashima Space Technology Center

nation use with large-diameter antenna, and (2) use of wideband data acquisition and wide frequency range. The first measure is based on the fact that the sensitivity of the VLBI observation is proportional to the product of the diameters of an antenna pair. The second measure improves the SNR and the delay measurement precision in the same way as for the VGOS system [5]. The observation specifications of the GALA-V are designed to be compatible with those of VGOS, so that joint observations will be possible. Details of the technology developments in the GALA-V project are described in the following sections.

2 Observation Specification of the GALA-V Project

Four 1-GHz bandwidth radio frequencies were determined as the basic VLBI observation mode for the GALA-V project: 3500–4524 MHz, 5100–6124 MHz, 9900–10924 MHz, and 13100–14124 MHz. Its data acquisition mode is 2048 Msps/1 bit/4 ch. We decided on these fixed observation frequencies at the start of the design and development of the GALA-V system, while the VGOS specifications require a flexible choice for the observation frequency bands. However, as explained in a later section, the real data acquisition system of the GALA-V system has some flexibility w.r.t. the frequency selection allowing joint observations with VGOS stations. The radio frequencies were selected taking into consideration results from a radio frequency interference (RFI) survey and choosing a fine delay resolution function formed by synthesizing the observed signals. The radio frequency spectra obtained in the RFI survey are shown in Figure 2. The broadband radio frequency survey for 3.5–18 GHz was performed at the Kashima, Koganei, and Tsukuba sites in 2012 using a broadband receiver system.

Taking into account these RFI survey results, the observation frequency array of 1-GHz bandwidth was allocated to have zero-redundancy spacing to form the fine delay resolution function. Our choice for the four frequency bands is separated by the ratio of 1:3:2 with multiples of 1.6 GHz. Figure 3 shows the delay resolution function expected to be formed with this frequency array. This is based on the assumption that the correlation amplitudes are uniform for all bands, although this has to be confirmed with real data.

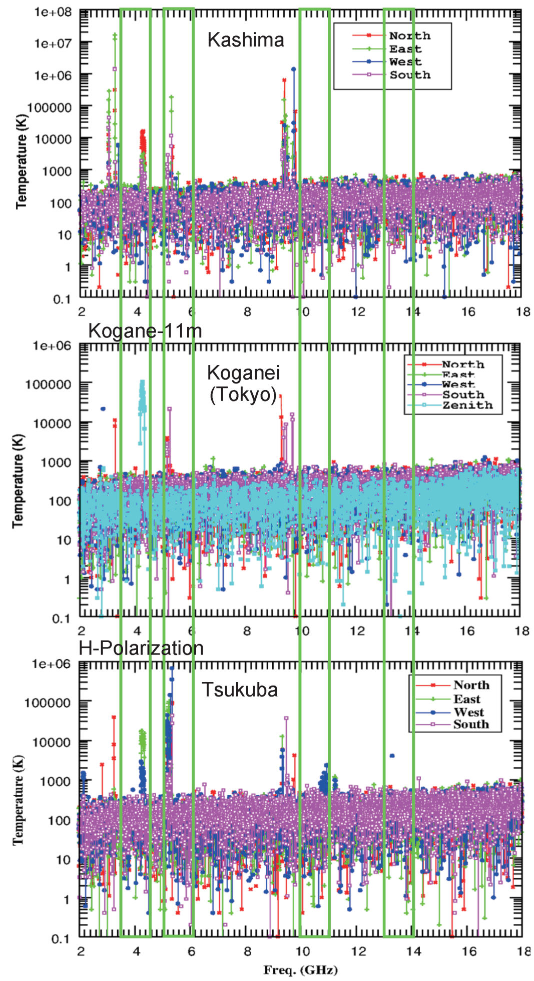

Fig. 2 Radio frequency spectra (MAX-HOLD) obtained in an RFI survey performed at the Kashima, Tsukuba, and Koganei sites in Japan. The received power is indicated by the antenna temperature in Kelvin. The broadband receiver system consisted of a double-ridged horn (SCHWARZBECK BBHA 9120 D), and room temperature LNAs (B&Z BZP118UD1 NF = 2 dB) were used in combination with HPF (Fc=3.5GHz Insertion Loss~ -0.3 dB) to avoid saturation due to strong RFI below 3 GHz. The amplified signal was fed into a spectrum analyzer (Rohde & Schwarz FSV30) and recorded. The measurements were made at four horizontal directions (NSEW) with a recording maximum value (RBW=1 MHz, VBW=1 MHz) during 30 seconds via the MAX-HOLD function of the spectrum analyzer. The four long rectangular boxes indicate the observation bands of the GALA-V system.

3 Small-Diameter Broadband Radio Telescopes

Small-diameter antenna system (1.6-m and 1.5-m diameters), each equipped with a Lindgren quad-ridge

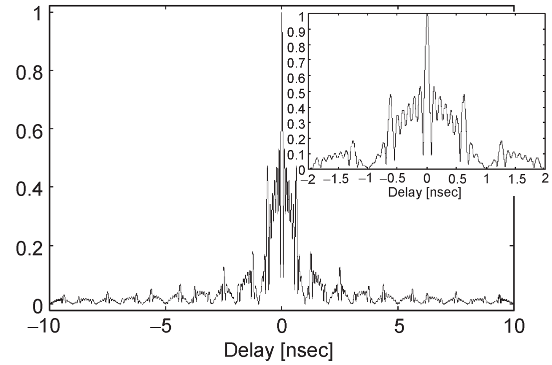

Fig. 3 Delay resolution function expected from the frequency array (3.5 GHz, 5.1 GHz, 9.9 GHz, and 13.1 GHz) with 1024-MHz bandwidth. The inset plot to the upper right shows a magnification of the center portion.

horn antenna (QRHA), are placed at Tsukuba (National Metrology Institute of Japan) and Koganei (NICT). The observation frequency of these antennas, which were originally developed for the MARBLE project [6], was modified from S/X -band to 3.5–15 GHz by exchanging the front-end microwave components. A broadband (1–18 GHz) optical signal transmission system with low noise figure characteristics (Sumitomo Osaka Cement, E18000) has been installed in place of the original frequency down-converter for both antennas. The phase calibration (PCAL) unit, whose pulse generation circuit was originally designed by Allan Rogers [7], was installed in the RF box of the antenna. The PCAL unit is used to generate 100-MHz intervals of frequency comb tones in the GALA-V system instead of the conventional 1-MHz interval. The reason for the 100-MHz interval is the improvement of the frequency characteristics of the PCAL signal, especially to get sufficient signal power at higher frequencies. Additionally, fewer injections of artificial signals are preferable to avoid an increase of the antenna system temperature. We believe that the 100-MHz interval tones will be enough for the phase calibration of 1024-MHz bandwidth and that a modern software correlator can handle any choice of PCAL frequency. The PCAL signal is an essential component for the calibration of the phase delay difference in the broadband bandwidth synthesis. The evaluation of the PCAL stability and phase behavior over the entire broadband is not sufficient yet and needs to be continued.

4 The Broadband 'Iguana' Feed for the 34-m Radio Telescope

One of the key issues of the GALA-V project is development of a receiver feed for a large-diameter antenna with long focal length. All of the broadband feeds currently known in the application to VGOS system have a wide beam size [8, 9]. This is one of the reasons why the ring-focus design was adopted for most of the new VGOS stations. We have started the development of a broadband feed of Cassegrain type for the Kashima 34-m parabolic antenna in 2012. The requested properties for the feed were (1) good efficiency at four frequency bands, which are described in the former section, and (2) constant and narrow beam width (HPBW $\sim 34^\circ$) for the target frequency bands. To satisfy these severe requirements, Dr. Ujihara investigated and proposed a new feed design. The new feed, called 'Iguana', is composed of two feeds: one for the higher frequency band and the other for the lower frequency band. At the end of 2013, a prototype of the higher frequency feed (Iguana-H) was mounted on the 34-m antenna with room temperature LNAs (Figure 4). The receiver system of the Kashima 34-m antenna is composed of four trolleys that are equipped with an S/X-band, L-band, C-band, and K/Q-band receiver, respectively. To change to a different receiver, the respective trolley is selected and moved up to the focal point of the antenna. The new Iguana-H receiver was installed in place of the C-band receiver system; thus, the S/X and other receivers were not changed at all and can be used as before. The lower panel of Figure 4 shows the SEFD and efficiency of the prototype feed. The Iguana-H feed demonstrated broad sensitivity over the frequency range 6–14 GHz. The development of the new broadband feed has been supported by a joint research development fund of the National Astronomical Observatory of Japan (NAOJ). The first light observation with the Iguana-H feed was made for the Methanol maser emission lines, which are known at 6.4 GHz and 12.3 GHz. The simultaneous observations of these two emission lines were performed for the W3OH maser source object on 17 January 2014 (Figure 5). Further improvement of the feed performance is under investigation for the final design, which is targeting good performance over the frequency range of 2–18 GHz. The broadband RF signal output from the front end is transferred to the observation room with a broadband optical signal transmission

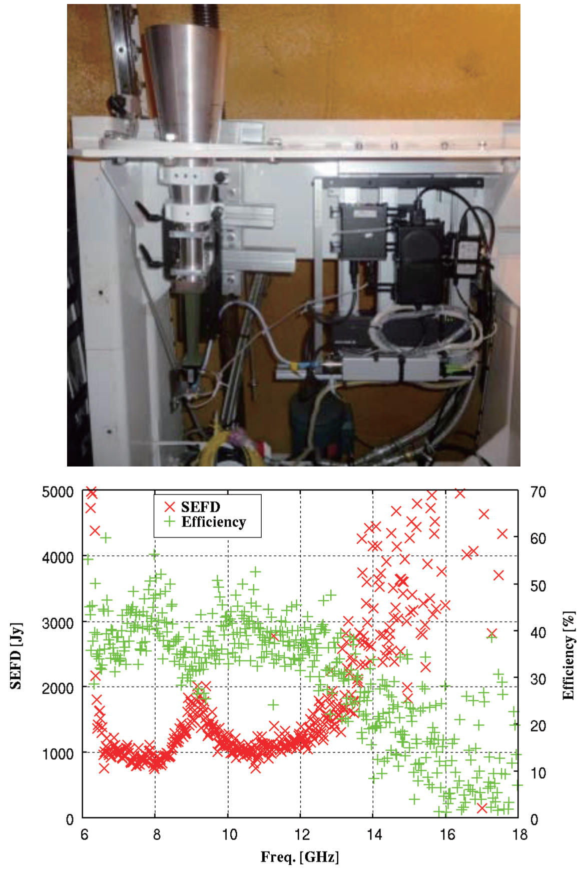

Fig. 4 A prototype of the higher frequency part of the broadband 'Iguana' feed was mounted on 34-m antenna (upper panel). System equivalent flux density (SEFD) and aperture efficiency measured with 'Cygnus-A' are indicated in the lower panel with '×' and '+', respectively.

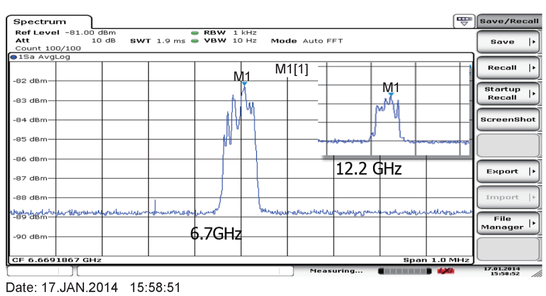

Fig. 5 The first light observation with the 'Iguana-H' feed was made on 17 January 2014 for the Methanol maser emission lines from W3OH at 6.4 GHz and 12.3 GHz, simultaneously.

system (E18000). The PCAL system of 100-MHz interval comb tones is to be injected after the LNAs via coaxial coupler, as is done with the small antennas.

5 RF Direct Sampler: K6/GALAS

One of the realizations of the data acquisition mode 2048 Msps/1 bit/4 ch uses a frequency converter, two sets of ADS3000+ samplers, and K5/PC-VSI (VSI-H) data recording systems. As another way for the data acquisition, employing a challenging new technology, we tried the direct sampling of the RF signal. The direct sampler K6/GALAS samples the analog RF signal at 16 GHz with 3-bit quantization; then frequency conversion and filtering is applied via digital signal processing. The data acquisition mode of 2048 Msps/1bit/4ch mode can be realized by one K6/GALAS sampler as indicated in the block diagram of Figure 6. The data stream over a 10G-Ethernet fiber link (10Gbase-SR) interface using the VDIF/VTP protocol and UDP/IP. The data recording system is composed of an off-the-shelf PC with 10Gbit Ethernet card and a Raid disk system. In addition to the simplicity and the reduction of the total cost, further benefits of the direct sampling approach are the homogeneous signal path length and the expected phase stability between the data at different frequency bands. Because the 'direct sampling' method captures the analog RF signal at once, the multiple frequency bands are separated by digital filtering. Thus, we can expect a uniform delay or an even delay adjustment between the data of each band. That might become advantageous for the broadband bandwidth synthesis. Further comparisons of the performance between the 'frequency conversion' and the 'direct sampling' methods have to be made using real data.

6 Remaining Tasks

An evaluation of the phase behavior of the 100-MHz interval PCAL signal and the frequency characteristics of the direct sampler remain to be done.

Correlation processing of the GALA-V project is performed with the GICO3 [10] software correlator developed at NICT. However, the post-correlation processing software is not ready yet. Synthesizing linear polarization correlation data and broadband bandwidth synthesis is a new feature of the bandwidth synthesis software. Data analysis is going to be done with CALC/SOLVE or C5++ [11]. The data processing path

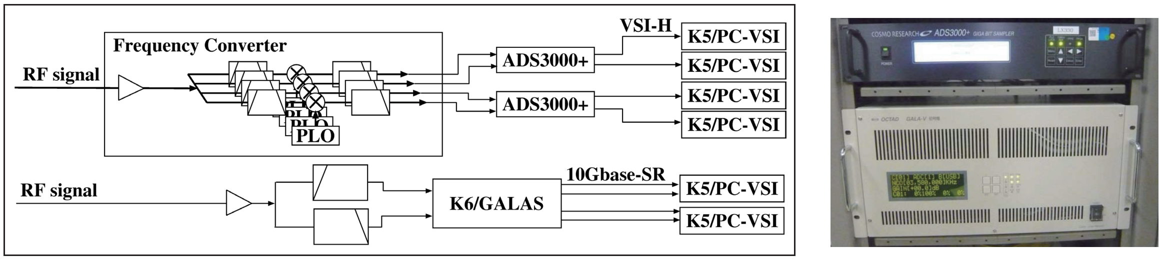

Fig. 6 Two ways of realizing the 2048 Msps/1 bit/4 ch data acquisition mode are illustrated in the left panel. The sampling frequency of the K6/GALAS is 16,192 MHz; higher and lower frequency signals than 8,096 MHz are separately input to avoid aliasing of the signal. The right panel displays a picture of the ADS3000+ sampler (top) and K6/GALAS (bottom).

from correlation processing to data analysis has to be established.

Acknowledgements

The broadband 'Iguana' feed development is supported by a Joint Development Research fund of NAOJ in 2013 and 2014. We thank Prof. K. Fujisawa of Yamaguchi University, Dr. M. Honma and Dr. N. Matsumoto of NAOJ, and Dr. H. Nakanishi of Kagoshima University for encouraging the development.

References

1. Riehle, F., Optical Atomic Clocks Could Redefine Unit of Time, Physics, vol. 5, Issue, id.126, 2012.
2. Jiang, Z, W., Lewandowski, Inter-comparison of the UTC time transfer links, Proc. of European Frequency and Time Forum (EFTF) 2012, pp.123-132, 2012.
3. Rieck, C., et al., VLBI and GPS-based Time-transfer Using CONT08 Data, Proceedings of IVS 2010 General Meeting "VLBI2010: From Vision to Reality", Edited by Dirk Behrend and Karen D. Baver NASA/CP-2010-215864, pp.365-369, 2010.
4. Rieck, C., et al., VLBI Frequency Transfer using CONT11, Proceedings of European Frequency and Time Forum (EFTF) 2012, pp. 163-165. 2012.
5. Petrachenko, B., et al., Design Aspects of the VLBI2010 System – Progress Report of the IVS VLBI2010 Committee, NASA/TM-2009-214180, 2009.
6. Ichikawa, R., et al., MARBLE (Multiple Antenna Radio-interferometry for Baseline Length Evaluation): Development of a Compact VLBI System for Calibrating GNSS and Electronic Distance Measurement Devices, Proceedings of the IVS 2012 General Meeting "Launching the Next-Generation IVS Network", Edited by Dirk Behrend and Karen D. Baver, NASA/CP-2012-217504, pp. 161-165, 2012.
7. Rogers, A. E. E., Test of new "digital" phase calibrator, BBDev. Memo #23, MIT Haystack Observatory, 25 Feb. 2010. `http://www.haystack.mit.edu/geo/vlbi_td/BBDev/023.pdf`
8. Yang, J., et al., Development of the Cryogenic 2-14 GHz Eleven Feed System for VLBI2010, 6th European Conference on Antennas and Propagation, DOI: 10.1109/EuCAP.2012.6206604, pp.621-625, 2011.
9. Akgiray, A., et al., Circular Quadruple-Ridged Flared Horn Achieving Near-Constant Beamwidth Over Multioctave Bandwidth: Design and Measurements, IEEE Trans. Antennas Propag., Vol. 61, No. 3, pp. 1099-1108, 2013.
10. Kimura, M., and J. Nakajima, 'The implementation of the PC based Giga bit VLBI system', IVS CRL-TDC News No.21, pp.31-33, 2002.
11. Hobiger, T., et al.,c5++ - multi-technique analysis software for next generation geodetic instruments, Proceedings of the IVS 2010 General Meeting "VLBI2010: From Vision to Reality". Held 7-13 February, 2010 in Hobart, Tasmania, Australia. Edited by D. Behrend and K.D. Baver. NASA/CP 2010-215864., p.212-216, 2010.