NICT Technology Development Center 2019+2020 Biennial Report

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Abstract The National Institute of Information and Communications Technology (NICT) is developing and testing VLBI technologies and conducts observations with this new equipment. This report gives an overview of the Technology Development Center (TDC) at NICT and summarizes recent activities.

1 NICT as IVS-TDC and Staff Members

The Communications Research Laboratory (CRL), which is the former name of the current National Institute of Information and Communications Technology (NICT), was designated as an IERS VLBI Technology Development Center (TDC) by the International Earth Rotation Service (IERS) in 1990. Since then, we have been continuously engaged in VLBI technology development for over 30 years, including the transition of designation name from IERS-TDC to IVS-TDC in 1999. As one of the activities of the IVS-TDC, we publish the newsletter "IVS NICT-TDC News (formerly, IVS CRL-TDC News)" at least once a year in order to inform the VLBI community about various VLBI-related technology developments in Japan. The newsletter series is available online at https://www2.nict.go.jp/sts/stmg/ivstdc/news-index.html. Table 1 shows the list of staff members contributing to this component.

1. Kashima Space Technology Center, National Institute of Information and Communications Technology
2. Usuda Deep Space Center, Japan Aerospace Exploration Agency

Table 1 Staff Members of NICT TDC as of January 2019 in alphabetical order.

HASEGAWA, Shingo	KAWAI, Eiji
KONDO, Tetsuro	MIYAUCHI, Yuka
SEKIDO, Mamoru	TAKEFUJI, Kazuhiro
TSUTSUMI, Masanori	UJIHARA, Hideki

2 General Information

The main topic of the 2019–2020 period was an intercontinental VLBI experiment for precise frequency comparison between Italy and Japan. The scientific results were reported by Pizzocaro et al. [1] and its analysis was reported by Sekido et al. [2]. Here we focus on the technical side of the experiments.

3 VLBI between Japan and Italy

We have carried out a series of geodetic VLBI experiments in 2018–2019 on an approximately 9,000-km baseline between portable 2.4-m VLBI antennas, named MARBLE. MARBLE1 was installed in Medicina, Bologna, Italy and MARBLE2 in Koganei, Tokyo. The Kashima 34-m antenna in Kashima was used as a reference station. We installed vertical polarization receivers at both of the MARBLEs and vertical and horizontal polarization receivers at the Kashima 34-m antenna. Four 1-GHz frequency bands specified within the total receiving range of 3.2 GHz to 14.4 GHz were simultaneously extracted; then, we observed 21–25 quasars repeatedly for about 30 hours in a single session. After the observation, linear polarization corrections were applied considering the parallactic angle and dispersive delay correction due to the ionospheric effect. As a result, we have successfully performed a bandwidth synthesis over the frequency range of 9.0-GHz width from 4.8 GHz to 13.8 GHz resulting in an effective bandwidth of 3.1 GHz.

4 Candidate Radio Sources

Correlated fluxes of most quasars are weak due to the 9,000-km long baseline between Japan and Italy. In a first test experiment, we chose good candidates from the radio catalog of the Astro-geocenter[1]. We picked up 115 radio sources, which have more than 1.0 Jy of total flux, from −10 deg to +90 deg declination, the 35% from the top in terms of total flux. In the series of frequency transfer sessions, about 27 sources were selected from ICRF sources by considering detected correlated flux in the observations.

5 Data Transfer and Correlation

A single session of the frequency comparison experiment lasted about 30 hours, and the amount of data for three stations was 240 TB (60 TB for a single polarization). We transferred single polarization data from Medicina to Kashima via UDT/IP protocol with jive5ab[2] at an average data rate at 5 Gbps. Then, correlation processing was performed by software correlator GICO3 as soon as the transfer finished. It took about one week for processing all scans of a single session. We routinely performed such sessions about 20 times.

6 Polarization Synthesis after Correlation

The large parallactic angle difference between Japan and Italy causes a misalignment of the linear polarization angle; consequently, this leads to a degradation of the signal-to-noise ratio (SNR). We needed to synthesize two polarization outputs to compensate the loss of SNR. The pseudo-Stokes-I observable is given by the

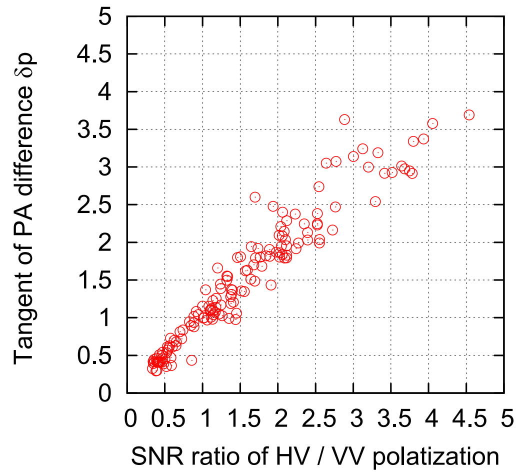

Fig. 1 A comparison of the SNR ratio of the polarization pairs of the Kashima 34-m and Medicina 2.4-m antennas and the tangent of the parallactic angles difference in a session.

following equation [5]:

$$I = \left(\overline{H_\mathrm{a} \star H_\mathrm{b}} + \overline{V_\mathrm{a} \star V_\mathrm{b}}\right)\cos(\delta p) + \left(\overline{H_\mathrm{a} \star V_\mathrm{b}} - \overline{V_\mathrm{a} \star H_\mathrm{b}}\right)\sin(\delta p).$$

Here, V and H indicate linear polarization with their suffixes corresponding to stations (a,b). δp is the difference of the parallactic angle between two stations. Since the compact antenna installed in Medicina has a single vertical polarization receiver, data of H_b is not available. Hence, we used half of pseudo-Stokes-I obtained by synthesizing two polarization cross products using the following equation:

$$I/2 = \left(\overline{V_\mathrm{a} \star V_\mathrm{b}}\right)\cos(\delta p) + \left(\overline{H_\mathrm{a} \star V_\mathrm{b}}\right)\sin(\delta p).$$

Figure 1 shows a plot of the tangent of parallactic angles difference between the Kashima 34-m and Medicina 2.4-m antennas versus the SNR ratio of the two polarization pairs in a session. The aligned data on a straight line is good evidence of the validity of the polarization synthesis procedure. Moreover, one more process was required prior to the polarization synthesis. The signal paths for two polarizations (V and H) of Kashima 34-m are slightly different. Thus, their correlation results involving the different delay needed to be corrected. Figures 2 and 3 show the comparison of group delay and phase delay between $\overline{V_\mathrm{a} \star V_\mathrm{b}}$ and $\overline{H_\mathrm{a} \star V_\mathrm{b}}$. Firstly, the group delay was corrected; then, the phase delay (or phase offset) had to be corrected.

[1] http://astrogeo.org/vlbi/solutions/

[2] https://github.com/jive-vlbi/jive5ab

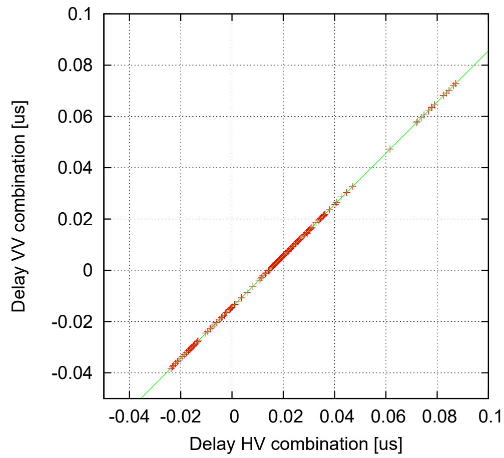

Fig. 2 A comparison of group delays between two polarization pairs (VH and VV) for the Kashima 34-m to Medicina 2.4-m baseline.

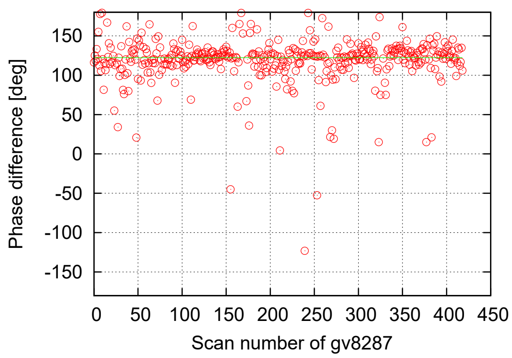

Fig. 3 Difference of phase delay between two polarization pairs (VH and VV) for the Kashima 34-m to Medicina 2.4-m baseline. The phase offset was empirically determined within 1 degree.

These processes were performed for all four 1-GHz bands correlation outputs to recover the efficiency, and the phase offset was determined within 1.0 degree. Figure 4 shows an example of the improvement of the fringe amplitudes by this polarization synthesis procedure. Thanks to the direct sampling system, no delay changes did happen during the series of observations. Once the delay difference between $\overline{V_a \star V_b}$ and $\overline{H_a \star V_b}$ was determined, it could be used for a few months (we did not evaluate how long it could keep the same state) and it was really helpful for our precise frequency comparison.

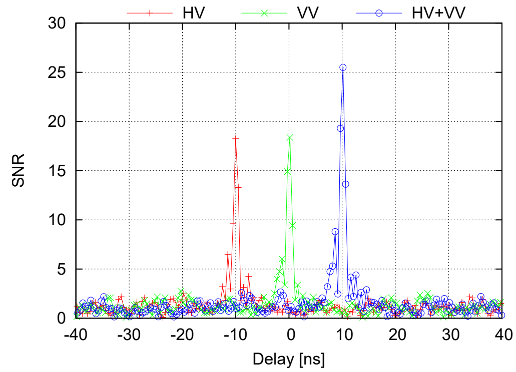

Fig. 4 An example fringe amplitude plot before and after the polarization synthesis for the Kashima 34-m to Medicina 2.4-m baseline. The SNRs improved from 18.3 and 18.7 for HV and VV to 25.7 for HV+VV after the polarization synthesis.

7 Wideband Bandwidth Synthesis with a TEC Search

An algorithm using the least-squares estimation based on a phase model was developed for determining TEC in the wide-band bandwidth synthesis (WBWS) processing [3]. The algorithm works well. However, it was difficult to apply this algorithm for data with an SNR lower than 10. In order to improve the TEC estimation at lower SNRs, we developed a TEC search-function method in addition to a least-squares (LSQ) estimation method [4]. The TEC search-function method performs iterative peak TEC search with applying several TEC values [5]. The one-sigma error, evaluated by comparison with a global ionosphere map (GIM) given by GNSS, was about 3 TECU on the Kashima–Medicina baseline (Figure 5). Even a 1.0-TECU difference causes group delay deviations as large as 17.2 ps [2]. Thus, it is important to determine accurate TEC values using a TEC search. Figure 6 shows the result of the iteratively searched TEC value on quasar 0133+476 with 110-sec integration on the Medicina–Kashima baseline. In the first step, we roughly apply TEC values from -50 to $+50$. Then, the final peak value is determined around the tentative peak value by a 2nd order polynomial fit (parabola fit). Figure 7 shows an example of a nice fringe plot after wideband bandwidth synthesis obtained with this procedure.

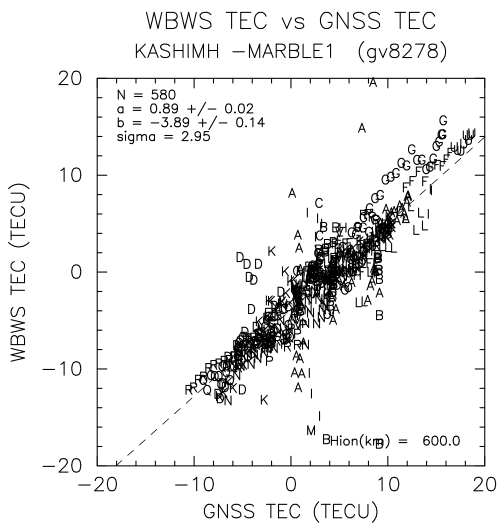

Fig. 5 A comparison between VLBI-based differential TECs by the TEC search-function method and those derived from a GNSS-based global ionosphere map. The data is for the 8,700-km Kashima–Medicina baseline.

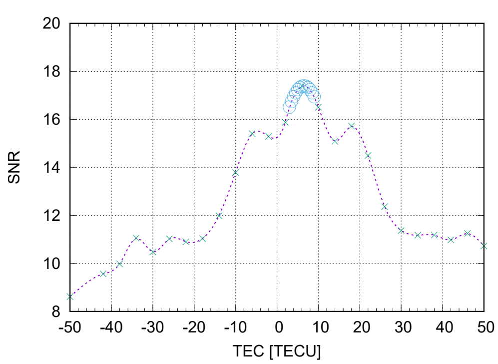

Fig. 6 Iterative search TEC peak on quasar 1144+402 in 60-sec integration on the baseline between Medicina and Kashima.

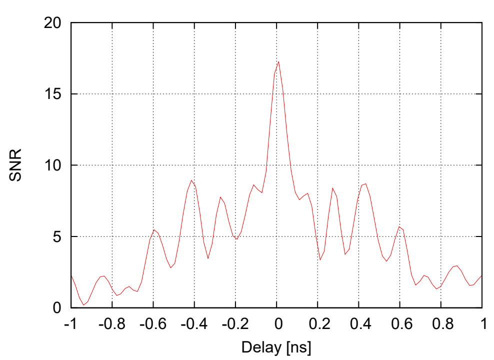

Fig. 7 A fringe plot of the same radio source as in Figure 6.

8 Development of Wideband Feeds and 2.4-m Antennas

The initial wideband feed for Gala-V, which was named IGUANA feed, was installed on the Kashima 34-m antenna at the end of 2013. The IGUANA feed was planned as a coaxial feed that is composed of IGUANA-H, a multimode horn for 6.5–16 GHz and IGUANA-L, the outer horn for 2.2–6.5 GHz. Following the installation of the IGUANA-H, the IGUANA-L was planned to be installed in later years [6]; however, the IGUANA-L was never manufactured, because the NINJA feed was newly developed for 3.2–16 GHz, which is an axial corrugated horn using lens and multimode for beam shaping. Advantages of the NINJA feed are reducing the numbers of LNAs, easy to change the beam width for other optics, and light weight; but there was a disadvantage in aperture efficiency. The radio interference under 3 GHz above S-band at Kashima was so loud and never would be quiet. Thus, in mid-2015 the IGUANA feed was replaced by the NINJA feed with OMT which can sharply cut incoming signals under 3.2 GHz. The Kashima 34-m antenna had a trolley system to exchange receiver horns. L- and S/X-band horns are set at the focal point of the antenna, but other horns are set with an offset to the focus and adjusted by the sub-reflector. Degradation by these offsets was estimated as several percent because of coma aberration.

The optics of the MARBLEs were changed from the initial 1.6-m or 1.5-m parabola dishes with Open-boundary Quad-Ridged Horn to 2.4-m Cassegrain with NINJA feeds to improve their sensitivity by three or four times. In all stations, the LNAs were not cooled because of a limited budget and development time.

The minimum frequency of the wideband feeds for Gala-V was set to 3.2 GHz. The Gala-V sampler had a maximum sampling rate of 16 Gsps and could sample RF signals up to 20 GHz; thus, the maximum frequency of the wideband feeds was planned up to 16 GHz (Figure 8). OMTs were designed for 3.2–14.4 GHz at both Port-0 and Port-1, and they had under −10 dB return loss (Port-0 can be used up to 16 GHz). If the feed and OMT had return loss over −10 dB, the near field measurement system would have made errors at the center of the calculated far field beam patterns.

The bandwidth of Gala-V is narrower than the feed and OMT, sampler, and signal transmission by RFoF

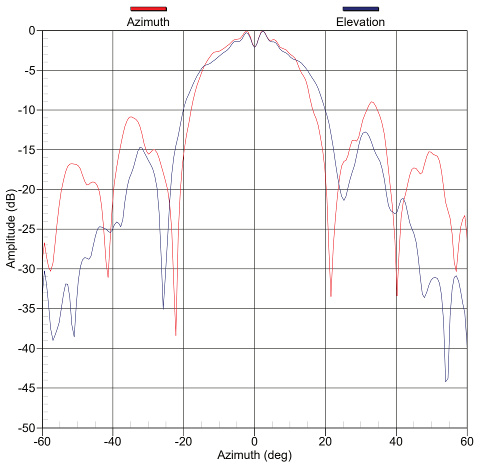

Fig. 8 Beam patterns of the NINJA feed for the MARBLEs at 16.0 GHz measured in METLAB of Kyoto University.

(RF over fiber). Maximum frequency was restricted to 14 GHz because MARBLE2 was located nearby TWSTFT (Two-Way Satellite Time and Frequency Transfer) antenna which radiates around 14 GHz for uplink. That signal was so strong to saturate LNAs of the MARBLE2. Thus, the MARBLE2 has a low-pass filter to cut TWSTFT signals and limits the frequency range used for Gala-V. Other in-band RFIs are suppressed by notch filters after LNAs at all stations, and a filter bank was added only in the MARBLE2 as a countermeasure to the RFI environment in Koganei. The filter bank of the MARBLE2 has 8-port branches and filters with different pass bands and path lengths are connected at each branch. Thus, the original phase response of the MARBLE2 receiving system is not linear over frequency. Also, OMT has different path length by 2.4 mm for Port-0 and Port-1; but Figure 2 shows a few meters of difference of path length. The RFoF in Kashima 34-m is a WDM (Wavelength Division Multiplexing) system (up to 26 GHz); thus the path length difference would come from the other part of the signal paths up to the sampler. These phase response and path length differences were compensated for in a calibration using a reference radio source.

The development of wideband antennas and VLBI activities in Kashima were terminated in 2021. But development of wideband antennas will be continued for SKA, BRAND, or other applications such as radiometers or satellite antennas in other laboratories in Japan. The 2.4-m diameter, small portable VLBI station (MARBLE) is the maximum dish size for marine container transportation. But it still has room for improvement using cooled LNAs for two or three times better sensitivity to enable VLBI observations of farther, fainter, and more compact objects. Also, high-temperature superconductor filters before the cooled LNAs may be effective to reduce RFI. Our broadband VLBI project took different oath than VGOS or SKA, like the evolution of the Galapagos Islands, but hopefully there is a marvelous future for broadband VLBI.

9 Future of Geodetic VLBI

Since the aperture areas of our compact antennas are so small, the intercontinental baseline observations with the Kashima 34-m telescope initially looked pessimistic. However, even such small antennas demonstrated nice results. Therefore, this approach may be a sustainable way for keeping on developing the large antennas. If other large, highly sensitive antennas join the observation, it improves not only the number of scans per session, but also the precise measurement of TEC; consequently, it leads to accurate results on long-distance frequency comparison and geodesy. We believe this approach might become an option for the future of geodetic VLBI.

References

1. Pizzocaro, Marco, Sekido, Mamoru, Takefuji, Kazuhiro, Ujihara, Hideki, et al., Intercontinental comparison of optical atomic clocks through very long baseline interferometry, *Nature Physics, Vol. 17*, pp.223-227, 2021. doi:10.1038/s41567-020-01038-6
2. Mamoru Sekido, Kazuhiro Takefuji, Hideki Ujihara, Tetsuro Kondo et al., A broadband VLBI system using transportable stations for geodesy and metrology: an alternative approach to the VGOS concept, *J. Geodesy,*, 2021, doi:10.1007/s00190-021-01479-8
3. T. Kondo and K. Takefuji, An algorithm of wideband bandwidth synthesis for geodetic VLBI, *Radio Sci., Vol. 51*, 2016. doi:10.1002/2016RS006070
4. T. Kondo and K. Takefuji, Current Status of TEC Estimation in the Wideband Bandwidth Synthesis Software, *IVS NICT-TDC News, No.38*, pp.11-14, Dec. 2019.
5. Roger Cappallo., Correlating and Fringe-fitting Broadband VGOS Data, *IVS 2014 General Meeting Proceedings*, 2014.
6. Ujihara, H., Development of wideband feed for Kashima 34 m Antenna, *Radio Sci.*, 18 APR 2017, doi:10.1002/2016RS006071