# Development of a Wide Bandwidth VLBI System at Kashima

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**Abstract** We have been developing a wide bandwidth VLBI system for Time and Frequency (T&F) comparisons. Two compact 2.4-meter antenna systems were installed and tested at NICT headquarters in Koganei, Tokyo and at the National Metrology Institute of Japan (NMIJ) in Tsukuba, Ibaraki until 2017. The two compact VLBI stations were indirectly connected via joint VLBI observations with the Kashima 34-meter antenna. In 2018, in collaboration with the Italian National Research Institute of Metrology (INRiM) and the Medicina VLBI station of INAF, we decided to relocate one compact antenna system to Medicina for T&F comparisons via VLBI observations between NICT in Japan and INRiM in Italy. The disadvantage of the lower sensitivity of the compact antenna is compensated for by the higher data acquisition rate, the wide frequency range of the observations, and the joint observations with a high sensitivity antenna. We have developed a broadband feed and a direct sampling system, allowing to use the frequency range from 3.2 to 14.4 GHz for VLBI observations.

**Keywords** Broadband VLBI, VGOS, T&F

## 1 Broadband System Development at Kashima

Three stations have installed a broadband frontend and backend system, consisting of a NINJA feed from 3.2 GHz to 14.4 GHz and a 16-GHz K6/GALAS direct sampler. Currently we have installed two types of broadband feeds at Kashima 34-m: firstly, since December 2013, an IGUANA-H from 6.5 to 15 GHz and, secondly, a NINJA feed from 3.2 to 14.4 GHz (SEFD $\sim$1,500 Jy) since July 2015. A modified NINJA feed 3–15 GHz was installed at all three stations in 2016. In paricular, the NINJA feed for the Kashima 34-meter radio telescope was specifically designed to realize a sharp beam pattern within 17 degrees to illuminate the sub-reflector. Two polarization sky signals after the amplifiers are transferred by optical converters with WDM to the observation room. We have installed a direct sampling system to make the entire system simple. The K6/GALAS direct sampler (see Table 1 for specifications) realized a relatively high-speed sampling at 16 GHz. After the quantization of the analog signals, the streams are digitally down-converted. Currently K6/GALAS has four ADCs, the first IF inputs the lower 8-GHz range and the second IF inputs the upper 8-GHz range, which covers the whole frequency allocation of VGOS [1]. Because the RF signal is directly digitized without analog frequency conversion, the phase differences between the output channels are fixed at the sampling stage. Thus, high precision delays can be derived with high stability by broadband bandwidth synthesis.

**Table 1** Specifications of the K6/GALAS direct sampler.

| | |
|---|---|
| Frequency range | 0.01 to 24 GHz |
| Number of analog inputs | 2 |
| Sampling rate | 16,384 or 12,800 MHz |
| Quantization | 3 bit |
| DBBC | 1-GHz bandwidth, 2 bit, 4 streams |
| 10GbE protocol | VDIF / VTP / UDP / IP |

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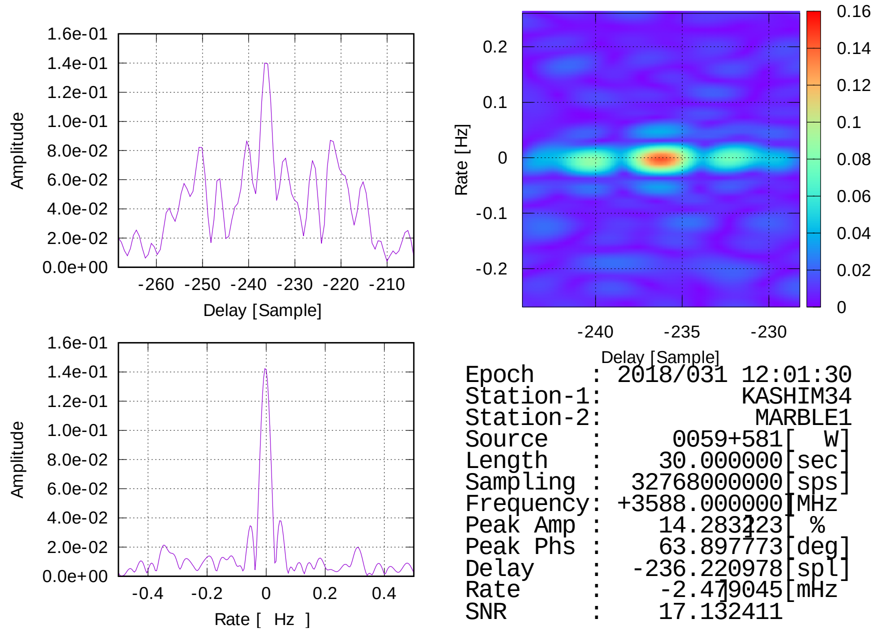


**Fig. 1** Fringe plot between the compact #1 and 34-meter antennas after wide bandwidth synthesis. The width of the delay resolution function is only 70 ps.

After the correlation, we determined a reference scan as a reference with a strong source from all scans for the wide bandwidth synthesis (WBWS). All scans were corrected using the reference scan; then residual delays and delay rates were estimated by calculating a search function. Finally, differential TEC values were estimated [2]. Figure 1 shows the fringe taken in early 2018 between the compact #1 and 34-meter antennas with the frequency sequence of 3.2 GHz, 4.8 GHz, 9.6 GHz, and 12.8 GHz. The compact antenna located in Koganei, Tokyo might have the worst RFI environment in the world. Then we adapted the system to the environment by several counter measures, such as installation of a feed with a sharp cut-off frequency, an analog filter bank system, and filtering after the software correlation, to reduce the impact of strong RFI.

## 2 Time and Frequency Transfer by VLBI

The National Institute of Information and Communications Technology (NICT) has not only been developing a VLBI observation system in its function as an IVS-TDC, but it also has maintained and kept the Japanese time standard. Recently NICT, AIST, and Tokyo University have been developing an optical-lattice clock for the next generation time standard towards the redefinition of “the Second.” Thus, it is necessary to compare with distant clocks of other countries on international baselines using several techniques. In case of two stations being as close as a few hundred kilometers, optical-fiber transmission is the best technique for the comparison. However, for distant station comparisons over thousands of kilometers a space technique is needed, e.g., GNSS, Two-Way Satellite Time and Frequency Transfer (TWSTFT), or VLBI. Thus, we would like to apply the VLBI technique to the intercontinental T&F.

With regards to the Time and Frequency transfer (T&F) by VLBI, the order of $10^{-16}$ in a few days is targeted. Since our two MARBLE antennas are quite small for VLBI, it is necessary to have a broadband system and to make effective use of it, e.g., by employing the VLBI Global Observing System (VGOS).

For the next-generation system of geodetic VLBI, VGOS was specified with fast moving antennas and broadband receivers. Several antennas that meet the VGOS requirements have been constructed (e.g., GGAO and Westford in the United States; one in Hobart, Australia and one in New Zealand; the

TWIN radio telescopes in Germany (Wettzell, TTW), Norway, and Sweden (Onsala, OTT); the RAEGE telescopes at Yebes in Spain and on Santa Maria in Portugal; three VGOS antennas of the QUAZAR network in Russia; and the Ishioka telescope in Japan).

NICT/Kashima is also developing a broadband system from 3.2 GHz to 14.4 GHz for the Kashima 34-meter antenna and two small and transportable antennas (see Figure 2). The broadband project is called "GALA-V."

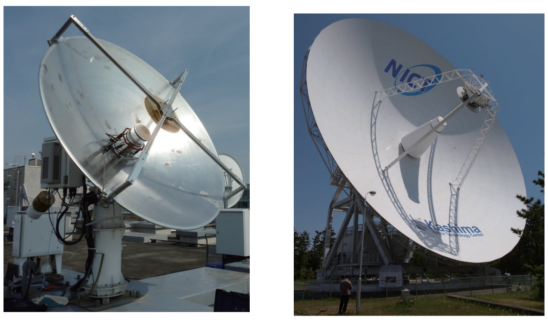


**Fig. 2** The broadband compact #2 (MARBLE2) in Tokyo (left) and the Kashima 34-meter antenna in Ibaraki (right).

We measure the frequency difference between the compact antennas by using the large telescope indirectly. The big advantage of adopting this method is that we omit the large telescope effects (e.g., gravity and thermal deformation, cable delay). When the large telescope is labeled O and two compacts are A and B, then the delay model between the two compacts can be expresseded as

$$\tau_{AB} = \tau_{OA} - \tau_{OB} - \dot{\tau}_{AB} \times \tau_{OA}. \qquad (1)$$

The delays that involve the large telescope $\tau_{OA}$ and $\tau_{OB}$ will disappear. Figures 3 and 4 show the $\pm 500$ ps clock behavior between each compact antenna and the 34-meter antenna for an experiment that was carried out in 2014. After performing the epoch conversion (Equation 1), the clock variation was reduced to $\pm 100$ ps in this case.

With regard to the postfit residuals after the subtraction of two delays $\tau_{OA} - \tau_{OB}$, the RMS of the residuals (typically 10 to 20 ps) shows almost the same value or it increased slightly. If the residuals are dominated by Gaussian noise, the RMS of the residuals will increase

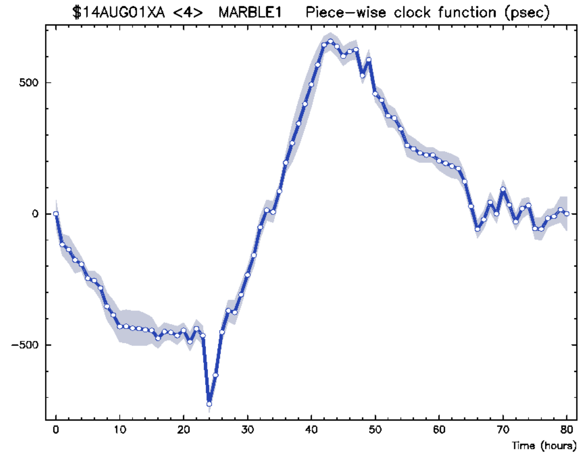


**Fig. 3** The clock behavior between compact #1 and the 34-meter.

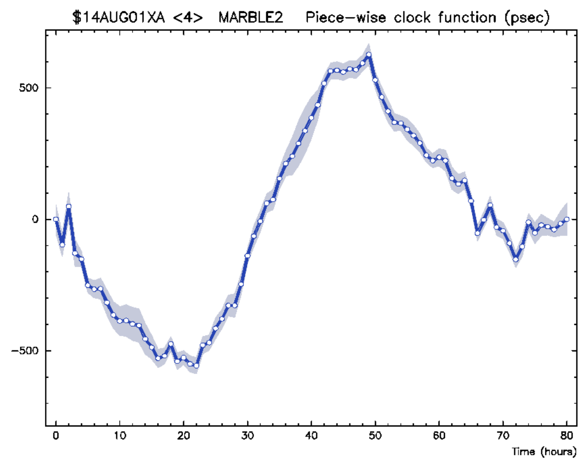


**Fig. 4** The clock behavior between compact #2 and the 34-meter.

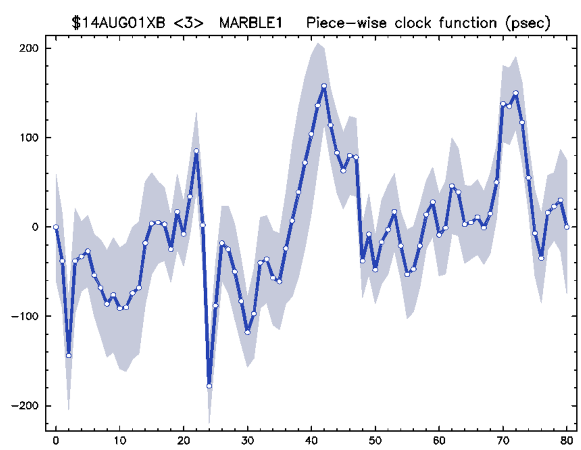


**Fig. 5** Clock behavior between compact #1 and compact #2 after subtracting Figure 3 from Figure 4 based on Equation (1).

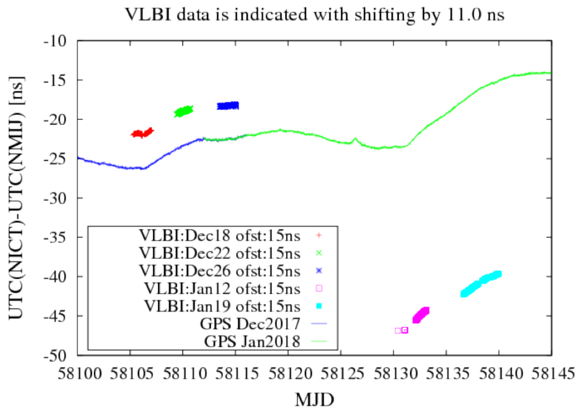


**Fig. 6** Clock comparison between GPS and VLBI for UTC(NICT)–UTC(NMIJ).

**Fig. 7** Relocated compact telescope in Medicina, Italy.

by a factor of $\sqrt{2}$. Therefore, we think that the residuals hit the atmosphere limit.

Figure 6 shows a clock comparison between GPS and VLBI for one month between NICT in Tokyo and NMIJ in Tsukuba. In this period, we carried out five 24-hour experiments with the wide bandwidth system. The data volume of the 24-hour observation amounts to about 150 TB (each station 50 TB). We performed a heavy correlation work for a few days. The VLBI result during the observation had a jump due to a feed replacement. However, once the system was fixed, we confirmed that the VLBI result had good agreement with GPS.

## 3 T&F between Japan and Italy

In the summer of 2018, we removed our compact telescope from Tsukuba and installed it in Medicina, Italy (Figure 7). Medicina and Turin are connected via optical fiber. The reference signal from INRiM in Turin can synchronize the Hydrogen maser in Medicina. The system works perfectly and the first fringe was obtained while we were still visiting Italy. We are now investigating compact and strong radio sources. We will carry out T&F measurements using VLBI starting in the fall of 2018.

## References

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