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# Study of an RF Direct Sampling Technique for Geodetic VLBI

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**Abstract**

Recently some digital samplers, which involve high RF frequency sensitivity, have been developed. We installed such samplers (sensitivity up to 24 GHz) at the Kashima 11-m station and the Tsukuba 32-m station (about 50 km baseline) in Japan and directly sampled X-band without any frequency conversion such as analog mixers. After the correlation process, we successfully detected first fringes at X-band. For the purpose of observing geodetic VLBI, we mixed signals of the S-band and the X-band just after the low noise amplifier. The mixed signal became overlapped and aliased baseband signals after 1024 MHz, 2-bit sampling. We could obtain four fringes (one from S-band and three from X-band), which came from the overlapped baseband signals, and successfully determined the baseline length.

## 1. Introduction

Radio signals from various radio quasars are detected in S-band (2 GHz) and X-band (9 GHz) in the conventional geodetic VLBI (Very Long Baseline Interferometry). The signal is converted to an IF (Intermediate Frequency) baseband signal from an RF (Radio Frequency) signal by mixing in a local oscillator signal. Then the IF signal is sampled by an A/D (Analog to Digital) converter. Generally most receivers consist of many kinds of analog hardware (e.g., amplifiers, filters, mixers, and other high frequency components including coaxial and optical cables). Thus, the path length of the signal from the antenna to the A/D converter is easily changed by temperature, and the group delay caused by variation of the path length is highly dependent on temperature in the same way.

To compensate for this group delay variation, the phase calibration system, which inserts 1 or 5 MHz step comb signals in RF frequency, is normally installed between the feed and the first LNA (low noise amplifier) to the geodetic VLBI antennas [6]. If the RF signals can be sampled just after the LNA, the group delay variation could be drastically reduced. Also it will reduce the cost of the geodetic VLBI system associated with converters and will increase the reliability of the system.

Recently it became possible to sample RF signals directly due to the progress of a sampling device. The ADX-831, which was developed by ELECS INDUSTRY CO. LTD., is an A/D sampler that has an input band width of 30 GHz[1]. We will install the ADX-831 at the Kashima 11-m antenna and the Tsukuba 32-m antenna, which are included in the global IVS network[2]. Then, we will detect the first fringes of the X-band signal in the RF frequency with this “direct sampling

[1]http://www.elecs.co.jp/ElecsIndustry/Product/HighspeedOperate/HighspeedADC.html
[2]http://ivscc.gsfc.nasa.gov/index.html

system" and without any frequency conversion by analog mixers. Next we will carry out a 24-hour geodetic VLBI session with the direct sampling system. The conventional geodetic VLBI records S-band and X-band signals which were sampled independently. However, we will combine S-band and X-band in the RF frequency and sample them as a single analog stream by using the aliasing of a digital signal technique. Our motivation is to establish an RF direct sampling technique and to pursue the possibility of using it in geodetic VLBI in the future. This paper follows Takefuji [4]; see there for more details.

## 2. RF Direct Sampling VLBI

### 2.1. Introduction of the RF Direct Sampling Technique for VLBI

RF direct sampling directly samples the RF frequency without any frequency conversions, as the name suggests. We first installed this RF direct sampling system at X-band at the Kashima 11-m antenna and the Tsukuba 32-m antenna to detect the first fringes which implies a well-correlated signal between two VLBI stations. Figure 1 shows the schematic diagrams of the system. The RF signal of the X-band after the LNA is brought down to our observation room via optical fiber. Then it is fed into the digital sampler with the remaining RF frequency through all backends and recorded at 1024 MHz speed.

Table 1. Specification of the digital A/D sampler ADX831.

| | |
|---|---|
| Frequency range of analog input | 10 MHz to 30 GHz |
| Number of analog input ports | 1 port (8192 Msps) or 2 ports (4096 Msps) |
| Sampling frequency | 8192 Msps |
| Quantifying bit number | 3 bits |
| 10GbE Optical connector | 10GBASE-SR, 10GBASE-LR, or 10GBASE-ER |
| 10GbE Protocol type | VDIF / UDP / IP |

The digital sampler ADX831, which has an analog input range up to 24 GHz, has the sensitivity to detect the signal of X-band (8-9 GHz)(see specifications in Table 1). According to the Nyquist theorem, twice the sampling speed (18 GHz sampling speed) is needed to detect the signal of the X-band. However, we sampled at a much slower 1024 MHz sampling speed because of a recording limit. Therefore under-sampling or high-order-sampling was adopted. The under-sampling is a technique of digital signal processing of a band-limited signal, where it is possible to detect a signal at a much higher frequency as a signal at a lower frequency. If we adopt a 1024 MHz sampling speed of the band-limited signal, we can obtain a 512 MHz bandwidth signal which is half of the sampling speed based on the Nyquist theorem. In the digital frequency domain after sampling, bands of 0 MHz to 512 MHz as USB (Upper Side Band) and 512 MHz to 1024 MHz as LSB (Lower Side Band) have a symmetrical shape with respect to the frequency at 512 MHz. And bands of 0 MHz to 512 MHz and 1024 MHz to 1536 (1024+512) MHz are the same side band and become exactly the same. We continue this until the X-band, 0 MHz to 512 MHz and 8192 MHz to 8704 MHz become the same bands. Here, the under-sampling plays a role in digital baseband conversion of the RF signal at X-band.

Now we only focus on the X-band of 8192 MHz to 8704 MHz. A lower and higher signal of this band is folded as unwanted noise. It is called aliasing. Generally an anti-aliasing filter (band pass filter specifically) will be inserted before the digital sampler to cut out the unwanted signals. However, since a purpose of this experiment was to detect fringes with the RF direct sampling system, we did not insert the anti-aliasing filter. Under the circumstances, the correlation amplitude will be reduced due to increased system noise, and more integration time will be needed. With this view in mind, we observed the radio quasar 3C84 with the Kashima 11-m and the Tsukuba 32-m stations and recorded the signal with 1024 MHz sampling speed and 2-bit quantization. After the correlation with GICO3, which is a software correlator developed by NICT, we could detect first fringes at X-band with the RF direct sampling system (see Figure 2).

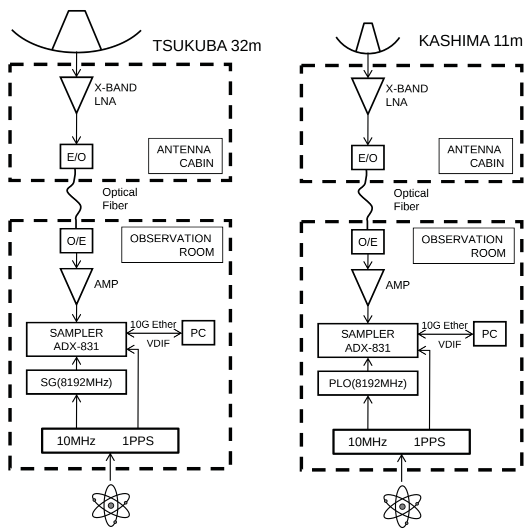


Figure 1. Schematic diagrams of the direct sampling VLBI at the Kashima 11-m antenna and the Tsukuba 32-m antenna. The signal from the LNA is transferred to the observation room through optical fiber and sampled without any frequency conversions.

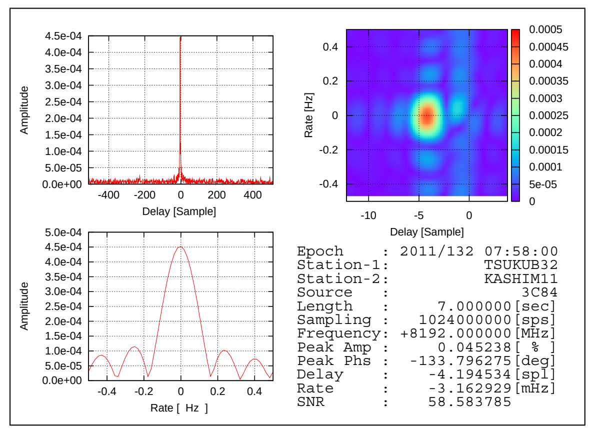


Figure 2. First fringes at X-band with the direct sampling system between the Kashima 11-m antenna and the Tsukuba 32-m antenna.

## 2.2. Development of the DSAMS as a Further Application for the RF Direct Sampling Technique for VLBI

Because aliased signals are perfectly mixed after sampling, we cannot generally restore the sampled and aliased signals to the original RF signal and recognize it as the original signal. Previously we only focused on the band of 8192 MHz to 8704 MHz and treated other folded bands as unwanted noise. However, these unwanted folded bands should include the signal of the radio sources. Detection of fringes from the folded bands between two VLBI stations is expected. Now we are going to explain a unique feature of VLBI. Suppose that two VLBI antennas which are located on the Earth's surface detect a radio signal from the quasars. Since the Earth's rotation causes Doppler shifts for each station at different locations, the RF frequencies of the radio signal from the quasars are different between the two antenna sites. The RF frequency shifts proportionally to the Doppler shift.

The highest frequency rate by the Dopper shift is about $2.42 * 10^{-10}$[s/s] at a 1 km East-West baseline (see [5]). This rate corresponds proportionally to the frequency shift of 1.94 Hz at 8 GHz. The baseline length of Kashima and Tsukuba is about 50 km East-West, and the corresponding frequency shift, depending on the angle of an observed radio source, will be several tens of Hz. Therefore, aliased signals at two stations at different locations are not the same.

## 3. DSAMS Applied in Conventional Geodetic VLBI

In this section, we will describe a further DSAMS technique for geodetic VLBI. Geodetic VLBI manages S and X-bands, where S-band is mainly used for an ionosphere correction and X-band is used for delay determination. Thus, we will combine the S-band and the X-band in the remaining RF frequency as a single analog stream as the further DSAMS technique. We inserted a BPF for the S-band to prevent strong RFI signals, but we did not insert an anti-aliasing filter into the X-band.

We carried out a 24-hour geodetic VLBI session with the DSAMS systems. For 24 hours, we observed a variety of radio sources several times. Each scan was fixed for 30 seconds, and the total number of scans was 945 scans. During observation, we recorded the combined RF signal at 1024 MHz speed and 2-bit quantization, and the total data was approximately 7.3 TB at one station. After correlation of the data from the two stations with GICO3, we could detect stable fringes from the S-band and from three X-bands. The average SNR of four bands during experiments are 117.2, 65.6, 145.7, and 77.7 for S-band, the low X-band, the mid X-band, and the high X-band respectively. 98 percent of the observations had SNR>20, which is a threshold SNR for geodetic VLBI.

Since we did not insert the anti-aliasing filter for the X-band, the fringe amplitude should decrease due to increased noise. However, the accuracy of the delay determination is proportional to the product of the SNR and bandwidth. Thus, we would recover the accuracy of the delay determination by bandwidth synthesis (BWS).

Generally the phase calibration system will be used to compensate for a group delay offset to connect narrow band channels. However, the sampled X-bands in DSAMS are the aliased and folded signals, and each folded band has no group delay and no physical phase offset. Therefore, we could connect the folded band as wider bandwidth smoothly without phase calibration system. Figure 3 shows an amplitude and a phase of the extended cross power spectrum after the BWS with KOMB [1]. After the BWS, the SNR improved to 11.7% better than the SNR obtained at the single X-band of 8192-8704 MHz.

We determined a quadratic curve of the phase, shown in Figure 3. Then we introduced the bandpass calibration (BPC) which is a well-known technique in radio astronomy. We chose a scan of the strongest radio source 3C84 in the session as a phase template. Figure 4 indicates the improvement with the BPC. The BPC improved the SNR on average more than 24.0% compared to the non-filtered X-band of 8192-8704 MHz. Finally we performed baseline analysis with Calc/Solve [2], and the baseline length between Kashima and Tsukuba was 5381281.71 mm.

## 4. Summary

We have developed new VLBI techniques for detecting fringes from directly sampled RF signals without any frequency conversions and we have detected fringes from even the aliased and folded

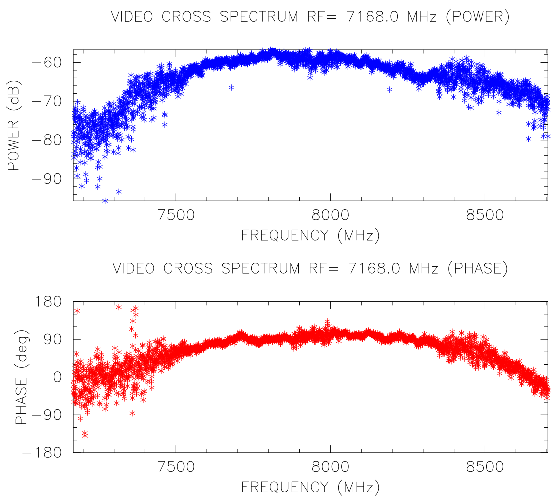


Figure 3. Extended cross spectrum from three 512 MHz bands in X-band after performing the bandwidth synthesis. The upper figure shows the amplitude, and the lower figure shows the phase.

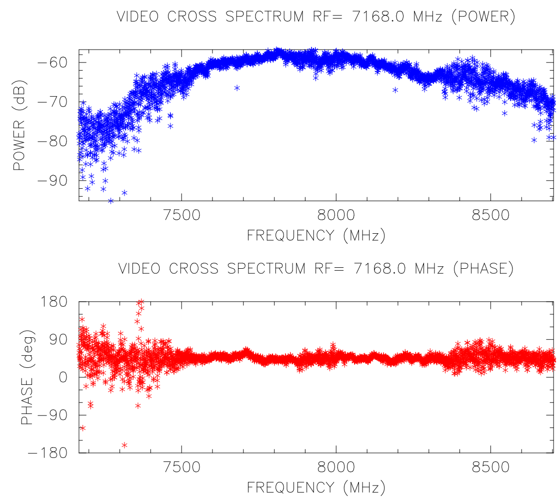


Figure 4. Extended cross spectrum after performing the bandpass calibration. A phase of cross spectrum of the strong source observation is used for subtraction as a calibrator.

band. We called this technique DSAMS (which means, direct sampling applied for mixed signals) with this unique feature dedicated to VLBI. For the purpose of geodetic VLBI, we combined the S-band and the X-band as a single analog stream with the remaining RF frequency. Consequently, we could detect the four fringes from the aliased signal, of which one came from the S-band and three came from the X-band. These fringes allowed us to estimate the baseline length between the Kashima 11-m antenna and the Tsukuba 32-m antenna even with bandwidth synthesis, the bandpass calibration, and the ionosphere correction with the S-band.

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