Publications of the Astronomical Society of the Pacific, **118**: 1739–1748, 2006 December

Development of a 4 Gbps Multifunctional Very Long Baseline Interferometry Data Acquisition System

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Received 2006 August 8; accepted 2006 October 13; published 2006 December 15

ABSTRACT. A 2048 Msps (megasamples per second) very long baseline interferometry (VLBI) data acquisition system (DAS) that has the ability to directly acquire intermediate frequency signals up to 1024 MHz bandwidth has been developed. By using these systems, 4 Gbps (4 gigabits per second = 2048 Msps, 2 bits) VLBI experimental observations were performed on 2005 November 25, and fringes were successfully detected with a newly developed software correlator. Both the data sampling rate (2 Gsps) and the total data rate (4 Gbps) were the highest rate ever used for VLBI observations. One of the applications realized with the DAS is differential VLBI measurements of deep space spacecraft, for which a wide-band recording is used for phase-reference quasars and a narrow bandwidth digital filtering is used for spacecraft. This paper describes the features of the developed DAS and cross-correlation system, results of the experimental observations, expected applications realized with the newly developed systems, and effectiveness of wide-band data acquisition for differential VLBI experiments for spacecraft navigation.

Online material: color figures

1. INTRODUCTION

High-speed data acquisition is one of the key factors for sensitive radio observations using VLBI. Wide-bandwidth data acquisition is as important as large-antenna aperture size in the sense of minimum detectable flux density expressed as $S_{\rm min} \propto (T_{\rm sys1} T_{\rm sys2} / A_1 A_2 \tau B)^{1/2}$, where $T_{\rm sys}$ is the system noise temperature at each station, A is the aperture size of each antenna, τ is the integration time, and B is the bandwidth of acquired signals. In addition, resolution of the measured delay observable in the geodetic VLBI observations is also proportional to the inverse of B. For these reasons, the NICT (National Institute of Information and Communications Technology) has been developing high-speed DASs by using state-of-the-art analog-to-digital (A/D) conversion technologies. The first 1 Gbps (1024 Msps, 1 bit) VLBI system was developed by Nakajima et al. (2001), using commercial digital sampling oscilloscopes and HDTV (high-definition television) video cassette recorders. Subsequently, a single-channel, 2 Gbps (1024 Msps, 2 bits) DAS—ADS-1000 (Nakajima 2003)—dedicated to VLBI was developed. Because wide-band intermediate frequency (IF) signals can be directly digitized with ADS-1000, IF distributors and analog baseband converters became unnecessary in the back-end system. Digitized IF signals are directly recorded by using RAID-based, high-speed, hard-disk recorders, or are transmitted to a correlator site in real time via a high-speed optical network. This VLBI system (K5/VSI system) is widely used at Japanese VLBI stations, especially for wide-band astronomical observations, playing an important role not only for continuum spectrum emission sources but also for the case of multiple line spectrum emissions over a wide range of frequencies. The VERA project of the NAOJ (National Astronomical Observatory of Japan) has used the ADS-1000 system, aiming to measure the position and proper motion of the Galactic masers to obtain a three-dimensional map of the Milky Way. In addition, it is used for wide-band, single-channel geodetic observations (Takaba et al. 2003) in which bandwidth synthesis is not used.

Unlike this unique wide-band data acquisition system in which IF signals are directly acquired, baseband converters with which multiple narrowband channels are extracted from IF signals are used in conventional VLBI systems, such as the Mark 5 system (Whitney 2006), which is widely used at the global VLBI stations. The NICT has also developed such a multichannel VLBI system, the K5/VSSP system (Kondo 2003), mainly for 16 channel geodetic VLBI experiments. Typical sampling rates of the system for each channel are 2, 4, 8, and 16 Msps. This system was installed at VLBI stations of the NICT, NAOJ, GSI (Geographical Survey Institute), JAXA

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(Japan Aerospace Exploration Agency), National Institute of Polar Research of Japan, Gifu University, Hokkaido University, and Yamaguchi University. These systems have been used not only for Japanese domestic geodetic VLBI sessions, but also for international geodetic sessions by means of a software-based format converter that converts K5/VSSP data files to Mark 5–compliant formats.

As a successor to these DASs, we developed a new K5/VSI DAS, named ADS-3000, which will be used for both single-channel, wide-band astronomical observations and conventional multichannel geodetic observations. It has two VSI-H–compatible (Whitney 2000) low-voltage differential signaling (LVDS) output ports, and each operates at a clock frequency of 32 or 64 MHz; the maximum output rate reaches 4096 Mbps. The main features are as follows:

1. The data sampling rate is increased to 2048 Msps, providing $\sqrt{2}$ times improved sensitivity for single-channel, wide-band astronomical observations compared with ADS-1000.

2. It has the capability of extending its function to digitally extract multiple baseband channels from input IF signals. The frequency difference between the lowest and highest frequency channels at X band exceeds 500 MHz in many international geodetic VLBI sessions conducted by the IVS (International VLBI Service for Geodesy and Astrometry). The data sampling rate is high enough to acquire the whole IF bandwidth for such geodetic sessions.

3. The number of quantization bits is increased to 8. While 2 bit quantization is enough for natural radio sources in conventional VLBI sessions, it is not enough for high signal-to-noise ratio (S/N) signals such as satellite down-link signals, or for single-dish power-measurement experiments such as pulsar-timing observations. This wide quantization bit depth allows it to be used not only for VLBI but also for a variety of other applications.

Specifications of the ADS-3000 are introduced in § 2. Results of the first experimental observations with the DAS are described in § 3. Both the configuration of the data recording system and phase-correction techniques required for wide-band, single-channel VLBI are also described in § 3. This DAS has a field programmable gate array based (FPGA-based) extensibility, enabling it to be used for a wide range of applications, which are discussed in § 4. Differential VLBI for spacecraft navigation is one of the most anticipated applications of the DAS; effectiveness of the DAS for such purposes is discussed. In § 5, conclusions and future plans are summarized.

2. DESIGN OF THE HARDWARE SYSTEM

In the DAS, 8 bit digitized data with a 2048 Msps, 10 bit A/D converter chip (Atmel, TS83102G0B) are sent to a 1-to-4 demultiplexer chip (Atmel, AT84CS001) to reduce the clock frequency enough to be processed (see Fig. 1). The less significant 2 bits of the ADC (A/D converter) output are not connected to the demultiplexer, in order to reduce wiring complexity. The 32 parallel, 512 Mbps output streams of the demultiplexer are sent to an FPGA device (Xilinx, XC2VP40), with the meander lines shown in Figure 1. The electrical length of each path is equalized with the meander lines in order to guarantee the data synchronization among the 32 parallel data streams. Inside the FPGA, each 512 Mbps serial input stream is demultiplexed to the 8 parallel, 64 Mbps bit streams; that is, sampled data that have an aggregate rate of 16 Gbps (2048 Msps, 8 bits) are divided into 256 parallel, 64 Mbps data streams. These data streams can be decimated with the FPGA to limit the total output rate within 4096 Mbps, the highest output rate realized with two VSI-H–compliant ports at a clock frequency of 64 MHz.[2] Although the maximum aggregate output rate is limited to 4096 Mbps, there is a trade-off between the sampling rate and the number of quantization bits. When the needed bandwidth is 1024 MHz (the Nyquist rate is 2048 Msps), streams corresponding to the most significant 2 out of 8 bits are selected and fed to the data lines of the two VSI-H output ports. When the input signals are band-limited with anti-aliasing filters, and the needed bandwidth is only 256 MHz (the Nyquist rate is 512 Msps), input data are decimated in time by a factor of 4 to 1, but all 8 bits are fed to the two VSI-H ports. All possible combinations of output parameters are listed in Table 1. Since the ADC chip has the sensitivity to input signals up to about 3.3 GHz, the higher order sampling method can be used. For instance, this digitizes signals in the 1024–2048 MHz band, where the upper frequency corresponds to the Nyquist rate. The band is effectively inverted during this process, which has to be taken into account in the phase convention of the interferometer. For another example, it is possible to directly down-convert and digitize the S-band radio frequency signals in the 2048–2560 MHz band, with the use of the 2-to-1 decimation with the FPGA. This method has an advantage in terms of gain and phase stabilities, because a down-conversion process can be done with no extra active devices. The FPGA device is easily programmable by inserting a CompactFlash (CF) memory card in which FPGA code is written to the CF slot on ADS-3000 (Fig. 2), so it can be used for multiple independent applications.

The main specifications of ADS-3000 are summarized in Table 2. The sampling clock frequency supplied to the ADC chip is fixed to 2048 MHz. The lower sampling rate becomes possible with the decimation function of the FPGA. The following main specifications of the ADC chip are listed in Table 2: number of effective bits, bit error rate, SFDR (spurious free dynamic range), input VSWR (voltage standing wave

[2] According to the VSI-H specification (Whitney 2000), a single VSI-H–compliant 80 pin connector has 32 LVDS data lines, and each operates at a clock frequency of 2, 4, 8, 16, or 32 MHz, with optional extension to 64 or 128 MHz. In the case of ADS-3000, this clock frequency can be selected from 32 or 64 MHz; therefore, each of two VSI-H–compatible ports has the ability to output the data at an aggregate rate of 1024 or 2048 Mbps.

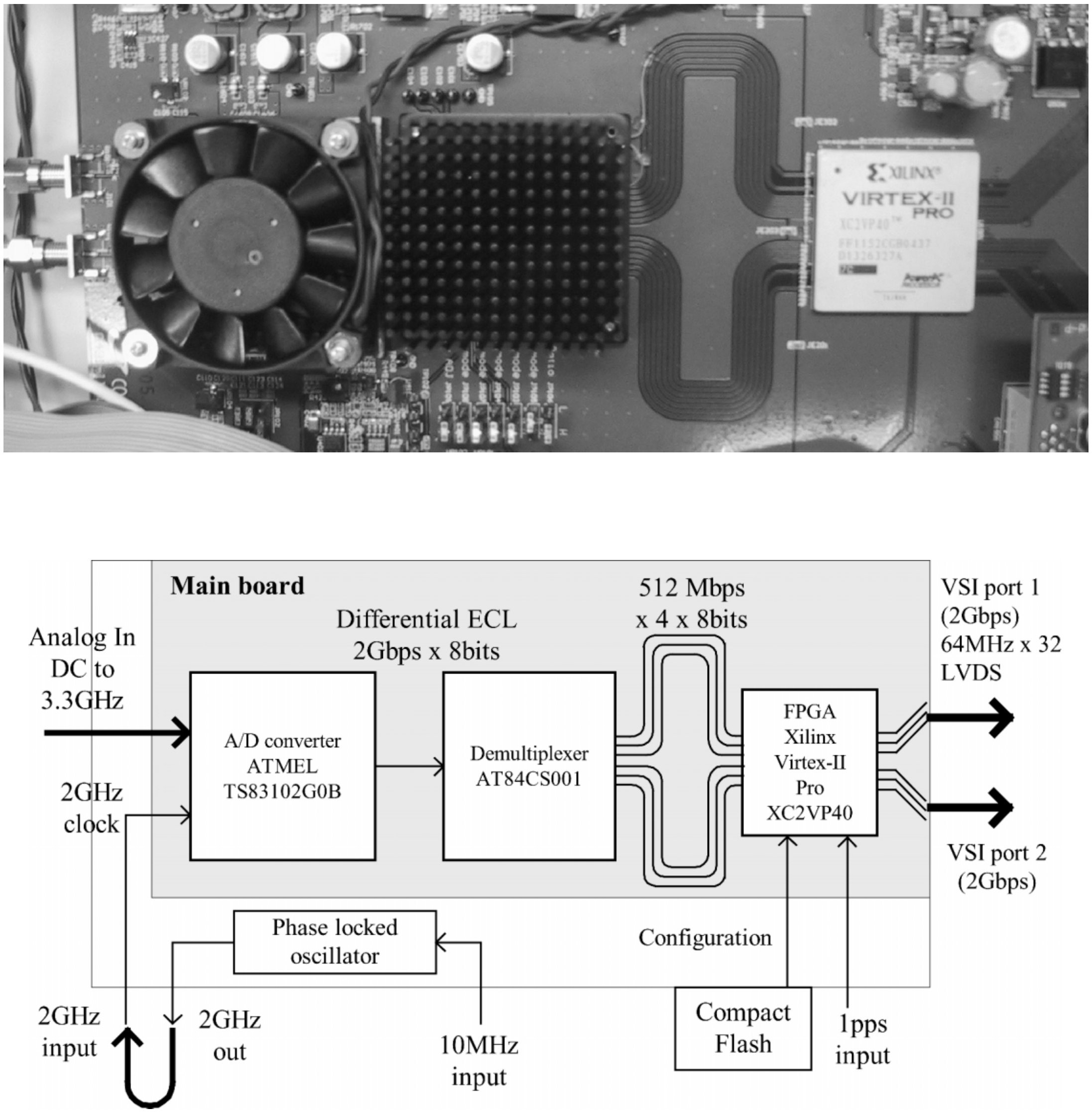

FIG. 1.—Schematic diagram of the ADS-3000 and photograph of the main board. [*See the electronic edition of the PASP for a color version of this figure*.]

TABLE 1
SELECTABLE OUTPUT MODES OF ADS-3000

Total Rate (Gbps)	Sampling Rate (Msps)	No. of Bits	Clock Rate (MHz)	Output VSI-H Ports
1 ………	128	8	32	Port1
2 ………	1024	2	32	Port1 (MSB) + Port2 (LSB)
	512	4	32	Port1 (upper 2 bits) + Port2 (lower 2 bits)
	256	8	32	Port1 (upper 4 bits) + Port2 (lower 4 bits)
	256	8	64	Port1
4 ………	2048	2	64	Port1 (MSB) + Port2 (LSB)
	1024	4	64	Port1 (upper 2 bits) + Port2 (lower 2 bits)
	512	8	64	Port1 (upper 4 bits) + Port2 (lower 4 bits)

NOTE.—There is a trade-off between the sampling rate and the number of quantization bits.

Fig. 2.—Front and rear view of the ADS-3000. FPGA logic is easily programmable with a CompactFlash card. A 2048 MHz PLL-output port and 2048 MHz input port are directly connected in most cases. A 2048 MHz reference signal can be distributed to other units using these ports. [*See the electronic edition of the PASP for a color version of this figure*.]

ratio), and gain flatness. SFDR is the ratio expressed in decibels of the rms signal amplitude, set at 1 dB below full scale, to the rms value of the next highest spectral component (peak spurious spectral component). SFDR is the key parameter for selecting a converter to be used in a frequency domain application. VSWR is defined as $(1 + S_{11})/(1 - S_{11})$, where S_{11} is the reflection coefficient of the scattering matrix. The VSWR over frequency measures the degree of mismatching between

TABLE 2
Main Specifications of ADS-3000

Parameter	Value
ADC sampling clock ……	2048 MHz (fixed)
ADC effective bits ………	6.5 for 2 GHz input (−1 dBFS)
ADC bit error rate ………	10^{-12} at 2 Gsps
ADC SFDR ………………	−54 dBc for 2 GHz input (−1 dBFS)
ADC input ………………	SMA-J, 0 ± 250 mV (peak-to-peak, 50Ω)
	3.3 GHz full power input bandwidth (−3 dB)
ADC input VSWR ………	1.2 max. (from DC to 2.5 GHz)
ADC gain flatness ………	±0.2 dB (from DC up to 1.5 GHz)
PLO phase noise ………..	100 Hz: up to 70 dBm Hz^{-1}, 1 kHz: up to 80 dBm Hz^{-1}
	10 kHz: up to 90 dBm Hz^{-1}, 100 kHz: up to 110 dBm Hz^{-1}
Reference signals ……….	1 pps signal, reference 10 MHz clock (0 dBm ± 3 dBm, 50Ω)
Digital output ………….	MDR: 80 × 2 (VSI-H–compliant, 32 MHz or 64 MHz)
Dimension ………………	88.1 mm (height) × 482.6 mm (width) × 430 mm (depth)
Power supply voltage ……	AC 100–230 V

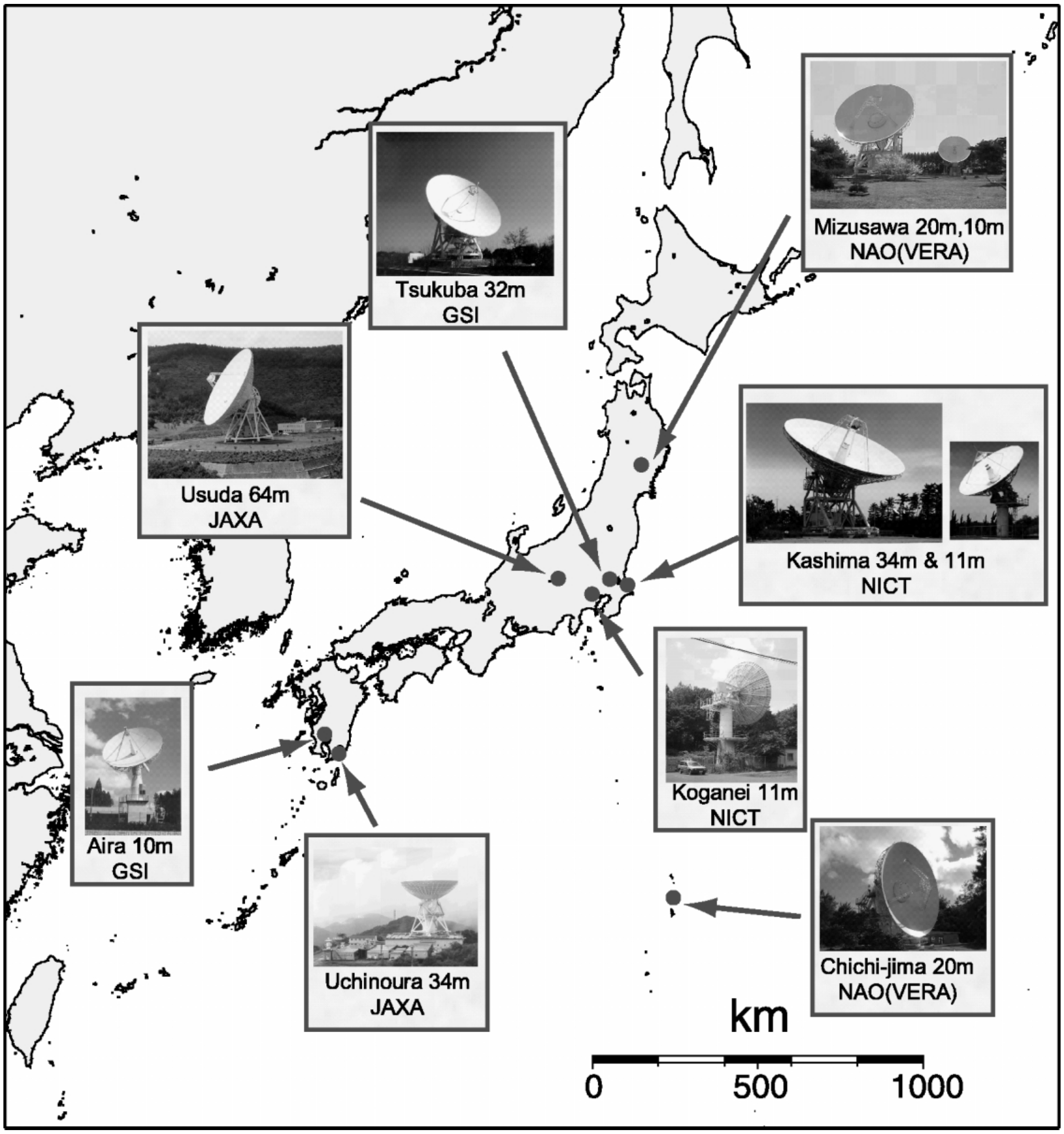

FIG. 3.—Japanese domestic VLBI stations participating in the differential VLBI experiments for the orbit determination for the *Hayabusa* spacecraft. [*See the electronic edition of the PASP for a color version of this figure*.]

the packaged ADC input impedance (ideally 50Ω or so) and the transmission line's impedance. The packaged ADC input impedance (transmission line and termination) is controlled so as to ensure VSWR < 1.2 : 1, from DC up to 2.5 GHz. A VSWR of 1.2 : 1 corresponds to a 0.039 dB insertion loss (20 dB return loss), i.e., 99% of the power transmitted and 1% reflected. See the Atmel TS83102G0B specification sheet for more details about the specification of the ADC chip.[3]

[3] See http://www.atmel.org/dyn/resources/prod_documents/doc2101.pdf.

3. OBSERVATIONS

The first 4 Gbps VLBI experimental observations were carried out by joining a VLBI session performed on 2005 November 25. The original purpose of the session was to demonstrate the performance of differential VLBI for the precise orbit determination of the Japanese *Hayabusa* spacecraft approaching the asteroid Itokawa, by using the K5/VSSP system. Japanese domestic VLBI stations that have participated in VLBI experiments for navigation of the *Hayabusa* spacecraft

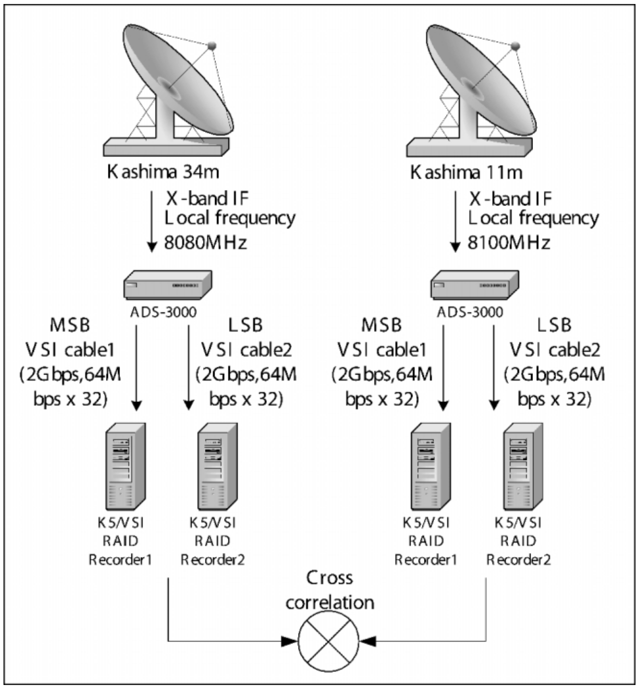

FIG. 4.—Schematic diagram of recording systems for the 4 Gbps VLBI experiments. [*See the electronic edition of the PASP for a color version of this figure.*]

are shown in Figure 3. Among these stations, 34 and 11 m antenna stations at Kashima were used for the experimental 4 Gbps VLBI observations in order to evaluate the capability of the newly developed ADS-3000 systems. In the experiment, the target source is switched between the *Hayabusa* spacecraft and reference quasars. The data analysis for the precise orbit determination is ongoing and will be reported in another paper.

3.1. Data Recording

The schematic diagram of the 4 Gbps recording system is shown in Figure 4. Instead of using baseband converters, wide-band IF signals were directly sampled with ADS-3000 and recorded at a rate of 4 Gbps. A 2 Gsps, 2 bit, wide-bandwidth sampling mode was used for the scans for quasars. A 512 Msps, 8 bit sampling mode was used to capture the relatively high S/N signals from the *Hayabusa* spacecraft. Because the current X-band IF bandwidths at both stations are limited, and frequency overlap between the two stations is only 450 MHz, the performed 2 Gsps, 2 bit sampling was not a Nyquist sampling but rather an oversampling by a factor of 2.27 ($=1024/450$). Two sets of 2 Gbps PC-based RAID VLBI recorders (K5/VSI recorder; see Kimura & Nakajima 2002) were used at each station to record the data; MSB (most significant bit) data streams and LSB (least significant bit) data streams were recorded separately in the independent recorders.

3.2. Correlator

A PC-based software correlator system was developed for the recorded data with ADS-3000. The correlator is a single-baseline FX-type correlator in which the number of fast Fourier transform (FFT) points can be set to an arbitrary number; it was set to 65536 for this experiment. The cross-correlation process for single-channel wide-band IF signals should take into account the following factors, which are not required for conventional narrowband video signals:

1. The frequencies of the first local oscillator are independent at each VLBI station; hence, the lowest frequencies of recorded data in the radio frequency domain are not always identical for each station, unlike in the case of the down-converted video signals. The frequency differences typically exceed several tens of MHz.

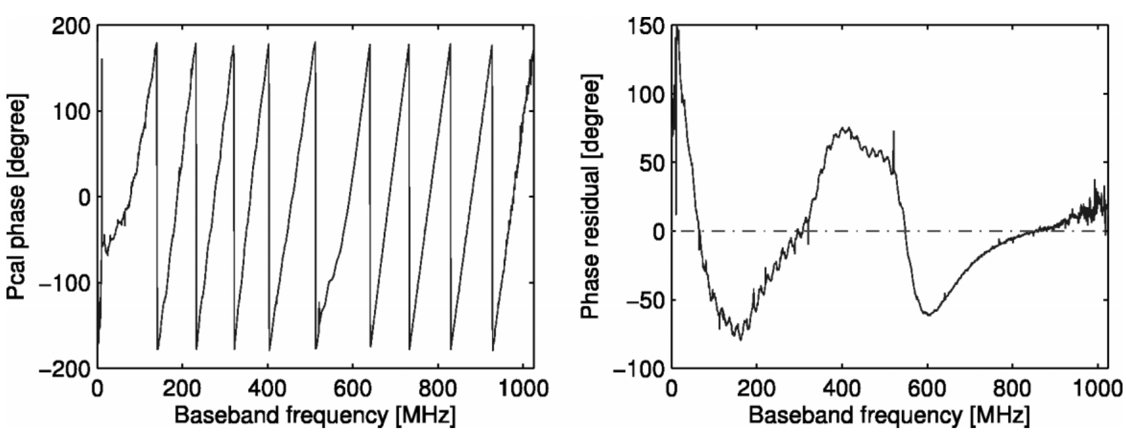

FIG. 5.—*Left*: Phase of 1024 phase-cal tones (0–1023 MHz) in X band at the Kashima 34 m station. *Right*: Residuals remaining after the linear fit of unwrapped phases of phase-cal tones. [*See the electronic edition of the PASP for a color version of this figure.*]

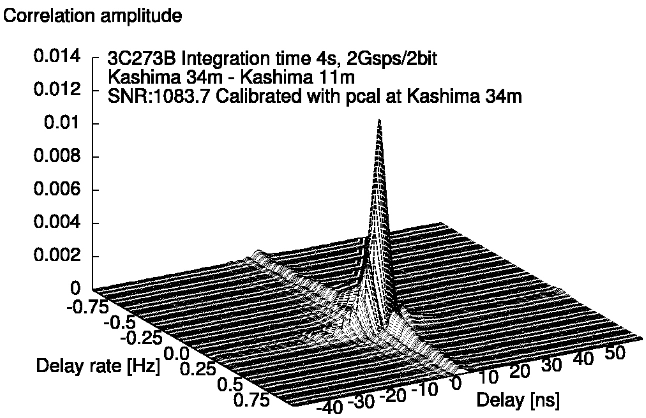

FIG. 6.—Detected 4 Gbps fringes between the Kashima 34 m and Kashima 11 m antennas at X-band observation toward 3C 273B on 2005 November 25. The integration time was 4 s. [*See the electronic edition of the PASP for a color version of this figure*.]

2. A wide-bandwidth coverage of IF signals can result in dispersive instrumental delay becoming significant, possibly resulting in a decreased S/N. Phase variations across the passband can be corrected in the cross-correlation processing by suitable calibration, provided the phase variations remain stable.

The first issue can be solved by shifting frequency channels of one of the stations, after the FFT processing in the correlator, by an amount corresponding to the difference of the lowest frequency. Phase variations across the passband are calibrated by using multiple phase-cal (phase-calibration) tones detected with the correlator. While phase-cal signals are usually used for multichannel VLBI in order to synthesize multiple fringe phases obtained with independent ADCs, it is also useful for the calibration of wide-band single-channel data acquired with a single ADC. The left panel of Figure 5 shows the detected phase-cal phases at the Kashima 34 m station during a 2 Gsps scan in the *Hayabusa* VLBI session. There were 1024 phase-cal tones within the 1024 MHz bandwidth of IF signals. Phase ambiguities of the tones can be removed by the phase-unwrapping process. If there are no dispersive instrumental delays, unwrapped phase-cal phases must be a linear function of frequency. The right panel of Figure 5 shows the phase residuals remaining after the linear fit of the unwrapped phase-cal phases versus frequency, representing overall characteristics of the antenna-based instrumental dispersive delays. The phase variations exceeded 50° within the IF bandwidth at the Kashima 34 m station. These phase residuals were interpolated by a spline function for every frequency channel in the correlator and multiplied for phase calibration. During the 4 Gbps VLBI session, phase-cal at the Kashima 11 m could not be used, so this phase-cal method was applied for Kashima 34 m data but not for Kashima 11 m data.

TABLE 3
THEORETICAL QUANTIZATION EFFICIENCIES AS A FUNCTION OF THE NUMBER OF QUANTIZATION BITS AND OVERSAMPLING FACTOR β (THOMPSON ET AL. 2001)

Rate	1 bit	2 bit
$\beta = 1$ (Nyquist rate)	0.637	0.881
$\beta = 2$ (2 times oversampling)	0.744	0.935

3.3. Observational Results

The first-ever 4 Gbps (2 Gsps, 2 bits) fringes obtained with the software correlator are shown in Figure 6. The vertical axis

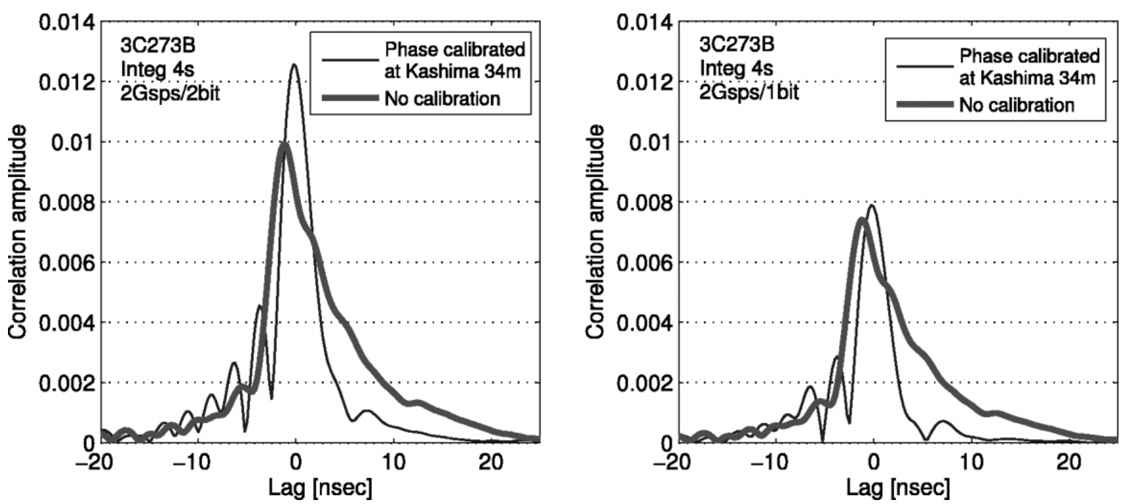

FIG. 7.—Amplitude comparison between the phase-calibrated and uncalibrated cross-correlation function. The left panel shows a result of 2 bit correlation, while the right panel shows a result of 1 bit correlation, in which only the MSB data stream was used. [*See the electronic edition of the PASP for a color version of this figure*.]

TABLE 4
Comparison between Results Using ADS-3000 and K5/VSSP for the Scan on 3C 273 in the *Hayabusa* VLBI Session

DAS	ADS-3000	K5 (CH1)	K5 (CH2)	K5 (CH3)
Sampling rate (Msps)	2048	8	8	8
Baseband frequency (MHz)	8100.00	8405.99	8535.99	8555.99
Number of bits	2	1	1	1
Bandwidth (MHz)	450	4	4	4
Integration time (s)	4	158	158	158
Correlation amplitude	0.0126	0.0113	0.0110	0.0153
Normalized amplitude	0.0143	0.0177	0.0172	0.0239
S/N	1083.7	400.9	389.8	542.0

Note.—Normalization factors in Table 3 were applied (0.637 for K5/VSSP and 0.881 for ADS-3000) to derive the normalized amplitudes.

represents the correlation amplitude as a function of delay and delay rate. A cross-sectional view along the delay axis near the peak position is shown in Figure 7. The thick lines in the figure represent uncalibrated results, which produce an asymmetric shape due to the instrumental dispersive delay. The thin lines represent results of phase calibration with phase-cal tones performed for the data of the Kashima 34 m station. Asymmetry was significantly reduced, and the maximum correlation amplitude increased 26% by the calibration. Peak position was shifted 1 ns. A full width at half-maximum (FWHM) of the resultant peak was about 3.5 ns, which was 1.5 times wider than the theoretical width of 2.2 ns ($=1/450$ MHz). This is considered to be due to the nonrectangular amplitude-frequency characteristics at each station and to the remaining dispersive delay components in the data of the Kashima 11 m station.

Data synchronization between MSB and LSB data streams recorded with different 2 Gbps recorders at each station should be checked in detail, due to its technical difficulty. For this purpose, we compared resulting S/Ns and correlation amplitudes between 2 bit and 1 bit correlations (using only MSB data streams) in the no-phase-cal case. As a result, the S/N using 2 bit correlation was 118% of that using 1 bit correlation. This is consistent with the theoretical value, 126% ($=0.935/0.744$), in the case of 2 times oversampling (see Table 3). In turn, the correlation amplitude using 2 bit correlation was 133% of that using 1 bit correlation (see Fig. 7). This is also consistent with the theoretical value of 138% ($=0.881/0.637$).

The correlation amplitude we obtained was compared with that found with the K5/VSSP system that was simultaneously used as a primary DAS in the session. Table 4 lists the results of the comparison. According to the results, normalized correlation amplitudes with ADS-3000 were 60%–83% of the amplitudes of the K5/VSSP system. The discrepancy can be considered to be due to the remaining uncorrected dispersive delay errors discussed above.

4. APPLICATIONS

By configuring the FPGA device in the DAS, a wide range of applications will be possible, such as a digital baseband converter for multichannel geodetic VLBI observations, a software demodulator for spacecraft down-link signals, or a spectrometer for broadband astronomical observations (see Table 5). Some applications can be realized with general-purpose IP (intellectual property) cores distributed by FPGA vendors. For example, an FFT (1K–16K points) core can be used for a wide-band digital spectrometer in single-dish astronomical observations or for a phase-cal detection circuit in a geodetic VLBI system.[4] A digital baseband converter (DBBC) is another expected application, which substitutes the conventional multichannel analog baseband converters that cause channel-dependent phase and amplitude fluctuations. If the input IF signals are band-limited and the 128 Msps mode is available, general-purpose IP-core products can be used for it.[5] To utilize the full 1 GHz band, the input signal to the DBBC should be multiplexed, and a dedicated parallel-processing digital mixer circuit in which the number of bits is lower than general-purpose ones should be used. Such FPGA-based DBBC systems dedicated to the back-end system of radio telescopes have already been devel-

[4] See http://www.xilinx.com/ipcenter/catalog/logicore/docs/xfft.pdf.
[5] See http://www.pentek.com/gateflow/gateflow_ipcore.cfm.

TABLE 5
Expected Applications and Usable FPGA IP Cores

Applications	Usable IP Cores
DC-cut, RFI mitigation	Subtractor, FIR filter
DBBC	DBBC, FIR filter, DDS
Spectrometer, wide-band phase-cal detector	FFT, integrator
Format converter (K5, Mark 5, PC-EVN, etc.)	CRC, look-up table
Dispersion compensator for pulsar observations	FFT, complex multiplier
Software receiver for satellite communications	FIR filter, DBBC

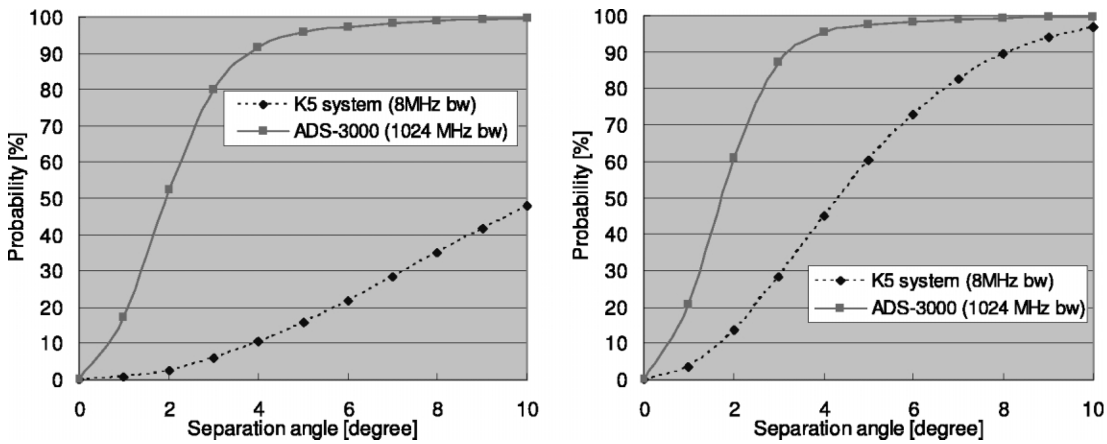

FIG. 8.—Relationship between the assumed acceptable separations between target spacecraft and reference quasar vs. the reference quasar's existence probability. The vertical axis is the existence probability of the reference quasar that can be detected (S/N > 20) within the integration time of 60 s. The left panel is in the case of the Kashima 34 m/Koganei 11 m baseline, and the right panel is for the Kashima 34 m/Tsukuba 32 m baseline. [*See the electronic edition of the PASP for a color version of this figure.*]

oped or used in several projects (Tuccari 2004; Xiang et al. 2006; Comoretto 2000). In the case where the start frequency of the baseband signal can be limited to an integral multiple of the bandwidth of the baseband signal, a simple decimation filter is applicable for the baseband conversion. This method requires fewer calculation resources and can be realized with a PC-based software method (Takeuchi 2004). A similar down-conversion technique is also used in the VERA system (Iguchi et al. 2005).

4.1. Usage in Differential VLBI Experiments for Spacecraft Navigation

Differential VLBI is a powerful tool for astrometry, with its high angular resolution. It is also effective for spacecraft navigation (Border et al. 1982) or precise tracking of space probes (Gurvits et al. 2006). NICT and JAXA have been cooperating on developing differential-VLBI-based orbit determination technology for Japanese deep space missions (Sekido et al. 2004), in order to improve the precision of the angular position of spacecraft. The DBBC function of the ADS-3000 will become a useful tool for such differential VLBI experiments. In the experiments, the target source is switched between spacecraft and phase-reference quasars in order to cancel out phase variations due to ionosphere, atmosphere, and instrumental delay at each VLBI station. To ensure a sufficient number of phase-reference quasars near the spacecraft, wide-bandwidth IF sampling is effective, since it can improve the sensitivity of the system. On the other hand, DBBC is useful for spacecraft observations because the bandwidth of spacecraft signals is very narrow. Using the digital BBC system, total data size can be reduced, and the S/N of the data can be improved for the narrowband spacecraft signals. Furthermore, it is easy to compensate for the Doppler shift of the spacecraft signals by real-time tuning with the direct digital synthesizer included in the DBBC circuit. Because the phase relationship is preserved through the baseband conversion process, we can use the delay of wide-band quasar signals as a phase calibrator for narrowband spacecraft signals. Note that phase fluctuations across the passband should be taken into account in the derivation of compensation phases for spacecraft from group delays of the reference quasars. The phase-cal method mentioned in § 3 can be used for this purpose.

In the current domestic differential VLBI experiments, the conventional analog down-converter and the narrowband K5/VSSP system up to 16 Msps have been used. Figure 8 is a result of a Monte Carlo simulation that shows the effectiveness of the installation of the wide-band ADS-3000 compared to K5/VSSP for typical Japanese VLBI stations. In the simulation, the direction of the spacecraft was selected at random on the celestial sphere (except for $\delta < -50°$), and we looked into whether a sufficiently strong reference quasar exists within a certain range of angular separations, using actual system temperature and aperture efficiency at each station. Reference quasars were selected from 2721 "acceptable calibrators" in the Very Large Baseline Array (VLBA) calibrator list (Kovalev et al. 2006). In differential VLBI, both a shorter switching time and a smaller separate angle are required for the effective removal of phase fluctuations. This simulation's result shows that a wide-band DAS is essentially required to find usable reference quasars within a few degrees of angular separations for typical Japanese VLBI stations.

5. CONCLUSION AND FUTURE PLAN

We have developed a VSI-H–compliant 2048 Msps DAS that is compatible with the other existing DASs. The first-ever 4 Gbps (2 Gsps, 2 bits) VLBI experiments were carried out using the DAS, and the fringes were successfully detected. Wide-band antenna-based dispersive delays were calibrated with phase-cal tones; consequently, the measured correlation amplitude was confirmed to be consistent with the results obtained with the conventional narrowband VLBI system. This DAS has an FPGA-based extensibility, enabling it to be used for a wide range of applications. We expect that it will be used not only for conventional VLBI observations but also for general-purpose data acquisition applications that require precise timing information. We will install an FPGA-based DBBC system to perform differential VLBI experiments for deep space navigation, in which wide-band IF signals will be directly recorded in the scans for reference quasars, and digitally extracted baseband signals will be recorded for the narrowband signals from spacecraft to measure phase delays.

The fastest current ADC operates at a sampling frequency of more than 20 Gsps (Nosaka et al. 2005; Murata et al. 2000), which is fast enough to directly capture radio frequency signals just after the first low-noise amplifier in conventional S- and X-band VLBI systems. When the performance of DBBC circuits improves enough to process the digitized high-speed radio frequency signals, using such devices will allow the receiver to be designed completely with digital components.

We would like to acknowledge the Cosmo Research Corporation[6] for constructing the ADS-3000 data acquisition system. We are grateful to T. Kato, M. Yoshikawa, Y. Murata, and N. Mochizuki of ISAS/JAXA (Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency), H. Kuboki of NICT, and members of other VLBI stations who participated in the spacecraft VLBI sessions for their assistance with the observations. We would like to thank the anonymous referee, whose insightful comments significantly improved this paper.

[6] For more information on the DAS, see http://www.cosmoresearch.co.jp.

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