Design and Development of a High-Speed Data-Acquisition System for the Korean VLBI Network

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(Received 2011 February 18; accepted 2011 June 25)

Abstract

A new high-speed Data Acquisition System (DAS) has been developed for the millimeter-wave VLBI array newly constructed in Korea, the Korean VLBI Network (KVN). The KVN DAS is specially designed to support the most distinctive feature of the KVN, that is simultaneous reception of multiple frequency bands (22, 43, 86 and 129-GHz bands in the current KVN system) for realizing multi-frequency phase referencing, which is the key technology for successful millimeter-wave VLBI observations toward active galactic nuclei and astronomical maser sources. Although the basic functions of the KVN DAS succeed technological elements originally developed in the VERA (VLBI Exploration of Radio Astrometry) Project, essentially new designs have been introduced for the simultaneous processing of four data streams in the optical data-transmission system, the digital filter, and the digital spectrometer. The KVN DAS system consists of four Gigabit Samplers (GBS), Optical Transmission System (OTS), Digital Filter Bank (DFB), Digital Spectrometer (DSM), and the data recorder. The DFB realizes very flexible and phase-stable channelization of up to four data streams. The DSM facilitates quick look of power and cross-power spectra of observed data. The VLBI output data from the DFB are recorded to the Mark5B recorder with a maximum rate of 1-Gbps. We discuss in the present paper the primary specifications, designs, and experimental results of the KVN DAS system.

Key words: instrumentation: interferometers—techniques: high resolution—reference systems: KVN DAS

1. Introduction

The Korean VLBI Network (KVN) is the first dedicated VLBI facility in Korea consisting of three millimeter-wave radio telescopes with 21 meter aperture diameter distributed in the Korean Peninsula. The maximum baseline length of the array is about 500 km (Kim et al. 2004). The primary scientific target of the KVN is the millimeter-wave VLBI, i.e., high resolution imaging of active galactic nuclei (AGN), Galactic non-thermal sources, and astronomical maser sources at millimeter wavelength. High-precision astrometry and geodesy observations will also be conducted with the KVN (Minh et al. 2003). Construction of the KVN was started in 2001 and completed in 2008.

The KVN employs a unique multi-frequency receiver system that enables us to observe a radio source simultaneously in up to four frequency bands: 22, 43, 86, and 129-GHz bands at present (Kim et al. 2010). The interferometric phase at lower frequency (22-GHz or 43-GHz) is used for compensating the phase at higher frequency (Han et al. 2008). We expect that this “multi-frequency phase referencing” will effectively remove the degrading irregular phase fluctuations due mainly to the turbulent troposphere, and will allow us to routinely conduct successful VLBI observations at frequencies as high as 86 GHz and 129 GHz.

The digital backend system for the KVN (KVN DAS) was newly developed for the realization of simultaneous processing of the multi-frequency waveforms received from a radio source. The KVN DAS consists of four Gigabit Samplers (GBS), the Optical Transmission System (OTS), the Digital Filter Bank (DFB), the Digital Spectrometer (DSM), and the data recorder. All of these instruments are connected through the VLBI Standard Interface (VSI) to ensure good connectivity with foreign instruments that could be added in the future.

The basic design of the DFB is based on the same principle as the VERA Gigabit Digital Filter Bank (GDFB) (Iguchi et al. 2005), except for the newly implemented input-data selection function, and the support of new observation modes
supporting the KVN multi-frequency receiving system. In addition to the VSI outputs, the DFB has a special ID-1 output port for the DIR1000 data recorder used in test VLBI experiments between Korea and Japan. The DIR1000 is the most popular data recorder widely used in Japanese radio telescopes.

In the OTS of the KVN DAS, four data streams corresponding to four Intermediate Frequency (IF) signals and a computer control signal are all merged into a serial data form, and then converted to an optical signal. In the VERA case, the OTS is introduced for transmitting the observed data only. The KVN DAS adopts more advanced communication technology, which allows one to transmit the observed data to the observation building and, at the same time, to realize computer control over the antenna-side instruments from the observation building through general optical channels.

The DSM of the KVN DAS is based on the FX-design and is equipped with new functions to produce both auto- and cross-correlation spectra of input data streams for measuring power spectra and cross-polarization spectra in the single-dish observations with dual-polarization receivers.

In this paper, we present the new KVN DAS. Basic concepts of the KVN DAS are briefly stated in section 2. Details of the KVN DAS architecture are given in section 3. Various test measurements conducted for the performance evaluation of the DAS, and their results are described in section 4. Section 5 summarizes this paper.

2. Basic Concepts of KVN DAS

The system configuration of the KVN DAS is illustrated in figure 1. Time control signals used in the KVN DAS, namely the station 1 Pulse Per Second (PPS) signal and the 10-MHz signal, are produced by the KVN clock system (Oh et al. 2007) based on the 5-MHz reference signal provided from the H-maser frequency standard. The 10-MHz signal is directly delivered to the gigabit samplers (GBS) at the antenna side through a distribution module. The station 1 PPS signal is used to set Coordinated Universal Time (UTC) to be attached to the digitized observed data by the GBS. The difference between the station 1 PPS and the Global Positioning System (GPS) 1 PPS signals is monitored and stored by a control computer. In the KVN DAS, the station 1 PPS signal is also transferred to the observation building through the VSI-compatible optical transmission system (OTS) fully conforming the definition of the VLBI Standard Interface.\(^1\)

Radio frequency (RF) signals received by the KVN receivers with 512-MHz bandwidth are converted to IF signals spanning a unique frequency range from 512-MHz to 1024-MHz and then digitized at the Nyquist rate. The KVN adopts the ADS-1000 GBS developed by the National Institute of Information and Communications Technology (NICT), Japan (Nakajima et al. 2000) as the analog-to-digital (AD) converter. Four ADS-1000 GBSs are installed in the antenna cabin of each KVN radio telescope. They are arbitrary connectable to 8 outputs (2 polarization components of 22, 43, 86, and 129-GHz bands) of the KVN multi-frequency receiving system. An ADS-1000 quantizes an IF signal in two bits with three decision levels at a rate of 1024-Mbps, thus producing a data stream of 2048-Mbps. In case of the multi-frequency observations, when four sky frequencies are received simultaneously, four data streams of 2048-Mbps rate with the total aggregated bit rate of 8192-Mbps are produced with the four ADS-1000s.

The digitized data streams are transmitted from the antenna cabin to the observation building by the Optical Transmission System (OTS). The OTS is composed of two parts, one installed in the antenna cabin, and another in the observation building. The part in the antenna cabin contains an Optical Transmission Unit (OTU) called optical transmitter

\(^1\) (http://www.vlbi.org/vsi).
optical fiber cable is completely free from any cable delay effect, since the signal phase is fixed at the moment of the AD conversion, and the following digital data transmission causes no damage to the phase. The transmission delay is just the traveling time of packets, and has no other important meanings.

The OTS transmits two different kinds of data frames: one contains the four observation data (2-bit sampled with 512-MHz bandwidth) sampled by the four ADS-1000 GBSs located in the antenna cabin transferred downward to the DFB in the observation building; the other carries the control signal running in both the upward and downward directions.

The part of the OTS in the antenna cabin is comprised of the OTX and the WDM. The OTX converts electric signals of VSI data to optical signals and the WDM combines (multiplexes) four optical signals with different wavelengths, and makes it possible to transmit them through a single optical-fiber cable. The other part of the OTS in the observation building is comprised of the WDM and the OTR. The WDM demultiplexes the four optical signals and the OTR retrieves the VSI data.

Figure 2 shows a functional block diagram of the OTS. An electric signal coming from a D-port of the OTU is first set to be aligned to an UDP/IP packet, and divided into ATM cells. The data ATM cells are merged with control ATM cells coming from a LAN port, and then converted to an optical signal (E/O conversion) after Synchronous Digital Hierarchy (SDH) framing. On the other hand, an optical signal input from an OI-port of the OTU is converted to an electric signal (O/E conversion). From the serial electric signal, a clock signal is retrieved and SDH de-framing is performed. The de-formatting process produces many ATM cells, which are routed to the data path and the control-signal path according to their ATM headers. Both types of ATM cells are disassembled to IP packets, i.e., data ATM to an UDP/IP packet and control ATM to a TCP/IP packet. The TCP/IP packet is used for the Local Area Network (LAN) connection of a control computer to individual units in the antenna cabin.

3. KVN DAS

3.1. Optical Transmission System (OTS)

As we already stated, the OTS is introduced in the KVN DAS mainly for transferring observed data from the antenna cabin to the observation building through an optical fiber cable. The development of the OTS was also motivated by an idea to directly connect the GBS outputs produced in the antenna cabin to a data center through an optical-fiber network provided by a general telecommunication company for achieving the electronic VLBI (e-VLBI) in near future.

The OTS has a great advantage over conventional analog transmission systems via coaxial cables, which are inherently accompanied by large and time variable cable transmission delays, often degrading the phase-sensitive interferometric observations. On the contrary, the AD conversion at the antenna side and the digital data transmission through an optical fiber cable is completely free from any cable delay effect, since the signal phase is fixed at the moment of the AD conversion, and the following digital data transmission causes no damage to the phase. The transmission delay is just the traveling time of packets, and has no other important meanings.

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3.2. Digital Filter Bank (DFB)

It is an important function of any VLBI DAS to pick up and record necessary frequency channels out of a wide received bandwidth, since scientific information is often spread over a wide frequency band, but the total recordable bandwidth is limited by the maximum rate of a recorder. For example, SiO

<table>
<thead>
<tr>
<th>Mode</th>
<th>Number of IF</th>
<th>Bandwidth [MHz]</th>
<th>Output streams</th>
<th>Bits/Sample</th>
<th>Output data rate [Mbps]</th>
<th>Output clock speed [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>KVN-1</td>
<td>1</td>
<td>256</td>
<td>1</td>
<td>2</td>
<td>1024</td>
<td>32</td>
</tr>
<tr>
<td>KVN-2</td>
<td>1, 2</td>
<td>128</td>
<td>2</td>
<td>2</td>
<td>1024</td>
<td>32</td>
</tr>
<tr>
<td>KVN-3</td>
<td>1, 2, 3, 4</td>
<td>64</td>
<td>4</td>
<td>2</td>
<td>1024</td>
<td>32</td>
</tr>
<tr>
<td>KVN-4</td>
<td>1, 2, 3, 4</td>
<td>32</td>
<td>8</td>
<td>2</td>
<td>1024</td>
<td>32</td>
</tr>
<tr>
<td>KVN-5</td>
<td>1, 2, 3, 4</td>
<td>16</td>
<td>16</td>
<td>2</td>
<td>1024</td>
<td>32</td>
</tr>
<tr>
<td>KVN-6</td>
<td>1, 2, 3, 4</td>
<td>8</td>
<td>16</td>
<td>2</td>
<td>512</td>
<td>16</td>
</tr>
<tr>
<td>KVN-7</td>
<td>1, 2, 3</td>
<td>64/128</td>
<td>2/1</td>
<td>1</td>
<td>1024</td>
<td>32</td>
</tr>
<tr>
<td>KVN-8</td>
<td>1, 2, 3, 4</td>
<td>32/64/128</td>
<td>2/1/1</td>
<td>1</td>
<td>1024</td>
<td>32</td>
</tr>
<tr>
<td>KVN-9</td>
<td>1, 2, 3, 4</td>
<td>32/128</td>
<td>4/1</td>
<td>2</td>
<td>1024</td>
<td>32</td>
</tr>
<tr>
<td>KVN-10</td>
<td>1, 2, 3, 4</td>
<td>16/32/128</td>
<td>2/3/1</td>
<td>1</td>
<td>1024</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 1. Observation modes with KVN DAS.
maser emission lines of different vibrational states ($v = 1$ and $2$) around 43-GHz are found within a frequency range of about 300-MHz, but the Mark5B recorder is capable of recording only a 256-MHz total aggregated bandwidth for 2-bit quantized data out of 512-MHz received bandwidth provided by the ADS-1000 GBS. This received bandwidth will be expanded to 1–2 GHz in the near future in view of a rapid advance of high-speed sampler technology. The DFB is introduced in the KVN DAS in order to flexibly channelize and extract necessary frequency bands according to the KVN observation modes listed in table 1.

One of the primary scientific targets of the KVN is the simultaneous observation of SiO maser emissions from an evolved star in different quantum transition states ($J = 1–0$, $2–1$, and $3–2$) at 43, 86 and 129-GHz bands. Also, simultaneous observations of maser emission lines from different molecules, H$_2$O and SiO for example, is another important target. Four receivers for 22, 43, 86 and 129-GHz bands and four ADS-1000 GBSs are introduced to conduct such observations. The DFB channelizes these emissions obtained from four receivers, and generates a 1024-Mbps combined output. The output data is delivered to the recorder and the DSM.

The KVN DFB is an enhanced version of the GDFB originally developed in the VERA Project (Iguchi et al. 2005). The VERA GDFB has two data inputs and core circuits are realized on the Application-Specific Integrated Circuit (ASIC). The enhanced DFB in the KVN DAS has four data inputs for four receivers and adopts the Field-Programmable Gate Array (FPGA) for core circuitry. The FPGA design allows one to reduce the development cost, and to easily upgrade the filter functions by changing the internal logics to keep up with future scientific requirements.

### 3.2.1. DFB configuration

The DFB hardware consists of a filter board and an output interface board. The filter board has four VSI input ports for four received data of 512-MHz bandwidth each, and sixteen filter units. Thus, the DFB accepts four 2048-Mbps input data (1024-Mps sampling with 2-bit quantization). The output interface board has two VSI output ports and one ID-1 output port with respective formatters. Through the two VSI output ports, the same data are transmitted to both the Mark5B (Whitney 2003) recorder and the DSM. Figure 3 shows a functional block diagram of a filter unit (a) and the framework of the DFB (b). As shown in figure 3a, the selected input sample phase is prepared for parallel processing of a digital filter, which has a symmetric FIR (Finite Impulse Response) structure, adopting half of the applied filter coefficients (see Iguchi et al. 2005). Multiplication with 1024-tap coefficients and accumulation of the results yields a bandwidth-limited data stream at a slower data rate with a 10-bit long sample size. Two-bit long samples are formed in the re-quantization unit at the best selected bit position specified by the maximum dynamic range of the samples. The output interface board transforms the two-bit re-quantized filter outputs to the VSI and the ID-1 data formats using corresponding formatters. Table 2 lists the functional specifications of the digital filter.

### 3.2.2. KVN observation mode

In the KVN observations, up to four frequency bands (22, 43, 86, and 129 GHz) are simultaneously received. Observers can use only one band, two, three or four bands in accordance with their scientific requirements. The DFB assigns these received signals to sixteen filter units with various combination of frequencies and bandwidths.

Table 1 lists all KVN observation modes defined in the KVN DAS.

The KVN-6 mode with 16 channels of 8-MHz bandwidth each is defined primarily for geodetic VLBI observations. The mode is just the same as the KVN-5 mode, except for the clock rate, which is a half of that in the KVN-5 mode. Geodesists prefer to assign up to 16 narrow band channels spread over a wide received band. Using the multi-channel data, they invoke the bandwidth synthesis technique to precisely estimate...
Fig. 3. Block diagram of the Digital Filter Bank (DFB). (a) Describes the data-processing flow in the DFB. (b) Shows the actual implementation of the DFB. The data selection module for four inputs are introduced to meet the requirements of the KVN multi-frequency observations.

Table 2. Digital filter specification.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter type</td>
<td>Symmetric FIR Filter</td>
</tr>
<tr>
<td>Input Sample rate</td>
<td>1024 Msps</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>512 MHz</td>
</tr>
<tr>
<td>Bits/Sample</td>
<td>2-bit</td>
</tr>
<tr>
<td>Data format</td>
<td>2-bit-32parallel-32Mclock(2048 Mbps)</td>
</tr>
<tr>
<td>Input selector</td>
<td>Select IF1/IF2/IF3/IF4</td>
</tr>
<tr>
<td>Output Sample rate</td>
<td>32 Msps</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>16 MHz (8 MHz)</td>
</tr>
<tr>
<td>Bit/Sample</td>
<td>2-bit (Re-quantization)</td>
</tr>
<tr>
<td>Data Format</td>
<td>2-bit-1parallel-32Mclock</td>
</tr>
<tr>
<td>Number of taps</td>
<td>1024-tap(even mode) / 1023-tap(odd mode)</td>
</tr>
<tr>
<td>Coefficient word size</td>
<td>13-bit</td>
</tr>
<tr>
<td>Down-sampling ratio</td>
<td>31:1</td>
</tr>
<tr>
<td>Clock speed</td>
<td>32 MHz</td>
</tr>
<tr>
<td>Sample phase select</td>
<td>0 to 30 (for parallel operation)</td>
</tr>
<tr>
<td>LSB position select</td>
<td>0 to 23</td>
</tr>
</tbody>
</table>

the geometric delay. It should be emphasized that the digital filter has a remarkable feature to preserve the signal phase. So far, analog video converters have been used to select up to sixteen narrow band channels from a wide-band IF signal. In such a case, uncertainty of the local oscillator phases makes it inevitable to use a phase calibration system to remove the LO-phase differences contained in the different video channels. Now, the bandwidth synthesis can be performed without the phase calibration system owing to the phase stable digital filtering.

Another remarkable feature of the KVN DAS can be seen in the KVN-7, KVN-8, KVN-9, and KVN-10 modes. These modes are specially defined for simultaneous multi-frequency observations with different bandwidths for different receiving frequencies. In the KVN-7 mode, for example, three receiver outputs can be assigned to two 64-MHz channels and one 128-MHz channel. In the KVN-8 mode, four receiver outputs can be assigned to two 32-MHz channels, one 64-MHz channel, and one 128-MHz channel. Such flexible selection of bandwidths for different frequency bands will be helpful when
the flux density of a continuum source varies in different frequency bands, or when various maser lines are observed in different quantum states.

3.3. Digital Spectrometer (DSM)

A spectrometer is indispensable for a VLBI telescope to conduct single-dish observations for system performance measurements (pointing, system noise, bandpass characteristics, etc.) and for various scientific studies (for example, monitoring of thermal molecular lines around maser sources). We present in this section system design and implementation of the Digital Spectrometer (DSM) adopted in the KVN. The DSM receives four 2048-Mbps (512-MHz bandwidth and 2-bit sampling) outputs of the four ADS-1000 GBSs and one 1024-Mbps (256-MHz aggregated bandwidth and 2-bit sampling) multi-stream output of the DFB. The DSM is capable of providing spectra with 4096 spectral channels for each of four GBS outputs with 512-MHz bandwidth, or up to eight channels with 256-MHz total bandwidth obtained from the DFB output. The FX-design (Thompson et al. 2001) is adopted for the KVN DSM.

3.3.1. DSM configuration

Figure 4 shows the framework of the DSM. The DSM has two FX boards and one control board. An FX board has two 2048-Mbps VSI input ports (Wide Input), receiving two out of the four GBS outputs, and one 1024-Mbps VSI input port (Narrow Input), receiving the 1024-Mbps multi-stream DFB output. The 1024-Mbps output of the DFB is duplicated and fed to the two FX boards in parallel.

An FX board consists of a data selection block (Narrow De-formatter, Wide 1:2 Stream Splitters, and Narrow/Wide Selector) and two correlator blocks. A correlator block consists of two FFT units called ‘F-sections’ and three (two auto- and one cross-) correlation units called ‘X-sections’ each followed by a ‘Bind or Select’ unit. Maximum processing rate of a correlator block is 512-Msps. Table 3 shows specifications of a correlator block. Actual implementations and operations of respective units are described in the following subsections.
The 8-K Fourier components are squared to form a power spectrum (auto-correlation) and multiplied with 8-K Fourier components coming from another FFT unit in the correlator block to form their cross-power spectrum (cross-correlation). The auto-correlation is used to see the power spectrum of the observed source. The cross-correlation aims at obtaining ‘depolarization’ of polarized signals received by a dual polarization receiver which has both Right Handed Circular Polarization (RHCP) and Left Handed Circular Polarization (LHCP) ports. All KVN receivers for 22, 43, 86, and 129-GHz bands are the dual polarization receivers.

After auto- and cross-correlations, the size of the frequency channels is reduced to half, from 8-K to 4-K, by the ‘selection’ and ‘bunching(binding)’ selection. The selection is an operation to place the spectrum alternately, and the bunching is the sum of adjacent frequency channels. The resultant 4-K spectrum is averaged in time over 102.4 milliseconds and then sent to a control computer. The computer performs longer integration depending on requirements of radio astronomers on the signal-to-noise ratio.

3.3.4. Operation mode

An FX board in the DSM is designed to be capable of calculating spectra of two 1024-Mbps (512-MHz bandwidth and 2-bit sampling) data streams in the wide band mode. Therefore, the two FX boards shown in figure 4 can process all four wide band data streams supplied by the four ADS-1000 GBSs. Since the processing speed of two FX engines in a correlator block is limited to 512-Msps, we introduce two correlator blocks in an FX board to achieve the 1024-Msps speed in terms of the parallel processing. The total eight FX engines are useful for processing the multi-stream data in the narrow-band mode as well.

For parallel operation in the wide-band mode, we use the Wide 1:2 Splitter in the data selection block of the FX board shown in figure 4. The Splitter acts as a foreground processor to build two FFT segments in one toggled cycle as illustrated in figure 7b. At every toggled cycle, two FFT segments are stored in a 32-K memory and then delivered to two FX engines in two correlator blocks. Connections of the outputs of the stream splitter to the FX engines are crossed, as shown in figure 7a. The cross connection is made for synchronizing two FFT segments in time and making cross-correlation possible.

Processing in the narrow-band mode is rather simpler than that in the wide-band mode described above. Eight FX engines in the four correlator blocks are one-to-one connected to eight streams from the KVN De-formatter (or Narrow De-formatter) in the data-selection block of the FX board shown in figures 4.
Fig. 7. Parallel operation of correlator blocks in the wide band mode of the DSM. (a) Block diagram of the parallel operation. (b) 1:2 Stream Splitter.

Fig. 8. Narrow-band mode operation of the correlator blocks in the DSM.

Fig. 9. Photo picture of the engineering test configuration of the KVN DAS. The Analog Noise Source Module (ANSM) is placed on the left table with the power meter, spectrum analyzer, and function generator. The clock distribution system (for 1PPS, 10-MHz synchronization signal), four ADS-1000 GRBs, Mark5B recorder, and the OTX with the WDM are placed in the left rack system. The OTR with the WDM, the DSM, and the DFB are placed in the right rack system. A local control system for the DAS is placed on the right table.

4. Experimental Results

In this section, we present results of experiments carried out for evaluating the KVN DAS. First, we present results of engineering tests of frequency responses of the DFB and the DSM. Second, we show results of single-dish observations of astronomical sources with 22/43-GHz dual receivers installed in the KVN 21-m radio telescope to see astronomical performance of the DSM and multi frequency functions of the KVN DAS. Third, in order to confirm the total performance of the KVN DAS for VLBI observations, we discuss the results of VLBI test observations.

4.1. Engineering Test

Engineering tests were carried out with a configuration shown in figure 9 to evaluate the KVN DAS performance. The test configuration mimics the KVN DAS system implemented in the antenna cabin and the observation building of the 21-m radio telescope. At first, the bandwidth characteristics of the KVN DAS were tested by using a test noise signal generated by the Analog Noise Source Module (ANSM) with 512-MHz bandwidth (512–1024 MHz).

In figure 10, panel (a) shows the frequency response of 512-MHz bandwidth measured by the DSM in the wide band mode, and other panels (b), (c), and (d) show frequency responses of the DFB outputs in KVN-2 (128-MHz bandwidth), KVN-3 (64-MHz bandwidth), and KVN-4 (32-MHz bandwidth) observation modes, correspondingly, processed by the DSM in the narrow band mode. The DSM was operated with 8K-point FFT for each frequency band. Therefore, a narrower bandwidth has a higher frequency resolution. The 8-K Fourier components are reduced by half in the DSM outputs, as we stated earlier. Figures 10b to 10d are composites of the 4-K point spectra of multiple data streams.
The wide-band spectrum in figure 10a and the combined narrow-band spectra in figures 10b to 10c show generally similar trends. However, we can see in figures 10b to 10c aliasing effects at the band edges. This indicates that the tap coefficients of the DFB have not been optimized.

After modifying the filter coefficients of the DFB, we obtained new results presented in figure 11. Figure 11 shows spectral shapes of the 22-GHz receiver signal (sky noise) obtained by the DSM in the wide band mode (a) and also in the KVN-1, 2, 3, 4, and 5 observation modes (b to f) of the DFB. Comparing the band edge results in figures 10 and 11, we figure out that the multi-stream spectra in figure 11 are more smoothly connected over the band edges than those in figure 10, as typically seen on the connections of streams 5, 6, and 7 in figure 11d (here the stream number are counted from left (lower frequency) to right (higher frequency). It is evident, however, that a noticeable gap still exists for example between streams 7 and 8 in figure 11d. This indicates that we still have a scaling problem which should be solved in future.

Secondly, we conducted two types of spectral analysis of the DFB outputs for a test signal composed of a noise signal and a continuous wave (CW) signal in the KVN-1, 2, and 3 modes, using the DSM in one case, and what we call the ‘Mark5B spectrum’ in another, respectively. We calculated the Mark5B spectrum in a computer for the data once recorded in the Mark5B recorder, using a software developed in the KVN Project. In order to reduce the data volume and the computation load, the recording and integration time was set to about 40 millisecond.

The spectra obtained in this experiment are shown in figures 12, 13, and 14. Note that the spectral shapes of even-number streams in figures 13 and 14 were reversed in the process of the digital filtering. Although we performed the same kind of experiment for the KVN-4 mode as well, we do not show the results here in order to decrease the size of the present paper.

Figure 12 shows results of the Mark5B and DSM spectra for the KVN-1 observation mode. The X-axis represents the frequency channels corresponding to the bandwidth from 0 to 256-MHz. The right peak is the CW input signal. We can see another peak in the left side, which is a spurious signal pattern produced by the ADS-1000. It is evident from figure 12 that the spectral shapes of the Mark5B and the DSM are quite similar to each other.

Figure 13 shows spectra of two streams in the KVN-2 observation mode with 128-MHz bandwidth each. X-axis shows frequency channels corresponding to the frequency bands from 0 to 256-MHz. The right peak is the CW input signal. We can see another peak in the left side, which is a spurious signal pattern produced by the ADS-1000. It is evident from figure 12 that the spectral shapes of the Mark5B and the DSM are quite similar to each other.

Figure 14 presents spectra of four streams in the KVN-3 observation mode with 128-MHz bandwidth each. X-axis shows frequency channels corresponding to the frequency bands from 0 to 128 MHz and from 256 MHz to 128 MHz, respectively. We see that spectral shapes both in Mark5B and the DSM are similar to each other and in good agreement with the shapes in the KVN-1 mode as shown in figure 12.
observation mode with 64-MHz bandwidth each. Again, the Mark5B and DSM spectra are similar to each other and in good agreement with those in figures 12 and 13.

From the above results of the engineering tests, we confirmed that the DFB, the DSM and the Mark5B recorder exhibit good performance in the bandwidth characteristics through the VSI connections. We expect that these experimental results will be helpful for solving problems to be possibly encountered in real observations.

4.2. Single Dish and Simultaneous Observation Experiment

In 2009, the 22-GHz and 43-GHz receivers were installed in KVN radio telescopes. Installation of 86-GHz and 129-GHz receivers is expected in near future. In order to evaluate
performance of KVN DAS in simultaneous multi-frequency observations, we carried out the test single-dish observations for simultaneous reception of SiO \(v = 1, 2, J = 1-0\) (43.122080GHz and 42.820587GHz, respectively) and H\(_2\)O 6\(16-5_{23}\) (22.235080GHz) maser lines with a 21-m radio telescope at Yonsei station of the KVN on 2009 June 5 (see Kim et al. 2010). Source I in the Orion KL star-forming region, known as a strong emitter of both SiO and H\(_2\)O maser lines, was selected for the target of the observation. We used cryogenic 22- and 43-GHz HEMT (High Electron Mobility Transistor) receivers, with typical receiver noise temperatures \(T\text{_{rx}}\) of 35 K (22 GHz) and 50 K (43 GHz), respectively. These receivers had dual polarization feeds. We used the circularly polarized feeds in our observation. The received signals were digitized by the ADS-1000 GBS and filtered by the DFB in the KVN-3 observation mode with 64-MHz bandwidth. The numbers of spectral channels for the 22-GHz and 43-GHz bands were set to 4096 and 2048, respectively. In the 43-GHz spectrum, 4096 spectral channels in the DSM output were reduced to 2048 by averaging two adjacent channels in order to get a better signal-to-noise ratio and almost equal velocity resolution with the 22-GHz spectrum. Thus, the resolutions are 0.21 km s\(^{-1}\) (15.63 kHz) at 22 GHz and 0.22 km s\(^{-1}\) (31.25 kHz) at 43-GHz, respectively. The DSM spectra were saved in a control computer and further integrated over around 4.5 min by means of the CLASS analysis single-dish software for continuum and spectral-line software.

All results of this test observation are given in terms of the antenna temperature, \(T\text{_{A}}\), measured by using the auto-correlation spectrum of a 300 K hot load as a reference. The corrections for the atmospheric attenuation and the elevation-dependent receiver gain variations were also applied. The conversion factors of the corrected antenna temperature, \(T\text{_{A}}\), to the flux density were about 11.07 Jy K\(^{-1}\) at 22-GHz and 11.55 Jy K\(^{-1}\) at 43-GHz, respectively.

Figures 15–17 show the successfully detected simultaneous spectra of the H\(_2\)O 6\(16-5_{23}\) and SiO \(v = 1, 2, J = 1-0\) maser lines in an unit of Kelvin for Y-axis.

4.3. VLBI Experiment

We conducted test VLBI observations between Yonsei and Ulsan stations of the KVN on 2009 October 16 and 22, in order to confirm the VLBI performance of the KVN DAS. Observed sources were a continuum spectrum source NRAO150 and Orion KL as listed in table 4. The KVN-5 observation mode with 16 streams of 16-MHz bandwidth each at 2-bit quantization was used in the test observation. Observed data were recorded in a DIR1000 recorder, which was used in the KVN commissioning observations with a combined array of
Table 4. Observation source for VLBI experiments.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Source</th>
<th>Observation frequency</th>
<th>Observation mode</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>KVN Yonsei, Ulsan</td>
<td>NRAO150</td>
<td>22 GHz</td>
<td>KVN-5</td>
<td>16 MHz</td>
</tr>
<tr>
<td></td>
<td>(Continuum)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orion KL</td>
<td>43 GHz</td>
<td>KVN-5</td>
<td>16 MHz</td>
</tr>
<tr>
<td></td>
<td>(Spectral line)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 14. Spectral shapes of the noise plus CW signal measured with the Mark5B spectrum and the DSM in the KVN-3 observation mode. Panels (a) and (c) show the Mark5B spectra in 0–64-MHz, 128–64-MHz and 128–192-MHz, 256–192-MHz bands, respectively. Panels (b) and (d) show the DSM spectra in the same bands as (a) and (b). Note amplitude scale is linear.

the KVN and the VERA. Correlation processing was made with the Mitaka FX correlator.

Figure 18 shows the detected fringe of a continuum source, NRAO150 in the delay and delay-rate coordinates at 22-GHz observation frequency. Only channels 9 and 10 of the KVN-5 observation mode with 16-MHz bandwidth each were selected form the DFB output and recorded to the DIR1000 recorder. The total bandwidth was 32 MHz for 128-Mbps recording. The first fringes detected between the KVN and the VERA were reported in Sohn et al. (2009).

Figure 19 shows the detected fringes of SiO maser spectral lines from Orion KL at 43-GHz observation frequency.
Fig. 15. Power spectrum of the H$_2$O maser emission in Orion KL obtained in the single-dish observation at 22-GHz band. Parameter values shown in the top of this figure stand for followings; l and b: Galactic longitude and latitude, Tau: Opacity at Zenith, Tsys: System noise temperature, Time: Total integration time (in minutes), El: Elevation of the source, N: Number of channels, I0: Reference channel number, V0: Velocity at the reference channel, Dv: Velocity resolution, F0: Rest frequency at the reference channel, Df: Frequency resolution, Fi: Image frequency at the reference channel.

Fig. 16. Power spectrum of the SiO maser emission in Orion KL obtained in the single-dish observation at the 43-GHz band.

These results clearly show good performance of the overall KVN DAS system in actual VLBI observations.

5. Summary

We have successfully developed the KVN DAS as a digital backend system in the new millimeter VLBI array, the KVN. The KVN DAS consists of ADS-1000 GRBs, the OTS including the WDM module, the DFB, the DSM, and the recorders. The KVN DAS has four input channels for processing four IFs for simultaneous multi-frequency observations, which is the most distinctive feature of the KVN among VLBI arrays in the world. The main cores of the DFB and the DSM were implemented in the FPGA for flexible upgrading of the system in the future. The DFB consists of sixteen digital filter units with 1024-tap lengths, just as the VERA terminal.

Fig. 17. Simultaneously observed H$_2$O and SiO maser line profiles in Orion KL in the multi-frequency single-dish observation at 22 and 43-GHz bands.

Fig. 18. VLBI fringe of a continuum spectrum source NRAO150 obtained on a baseline between KVN Yonsei and Ulsan stations at 22-GHz observation frequency.

Fig. 19. VLBI fringe of an SiO maser source Orion KL obtained on a baseline between KVN Yonsei and Ulsan stations at 43-GHz observation frequency.
However, the KVN DFB has a special input-data selection module introduced for multi-frequency observation. The DSM is based on the FX design, which is capable of processing 512-MHz bandwidth data in the wide-band mode and multi-stream data of 256-MHz aggregated bandwidth in the narrow-band mode. The entire interfaces in the KVN DAS were implemented with strong compliance to the VSI specifications as the first time in the world. We have installed the KVN DAS at all three KVN stations, and now successfully operate the DAS for VLBI and single-dish observations of the scientific objects of the KVN (Minh et al. 2003).

Only results for several KVN observation modes of the KVN DAS are presented in this paper, but we expect to have an opportunity to show performance evaluation results of whole KVN observation modes of the KVN DAS system soon.

Appendix. Expression of Fourier Transform Introduced in DSM Development

The N-point Fourier transform is expressed in the following equation:

\[ F(k) = \sum_{n}^{N} f(n)e^{-j \frac{2\pi nk}{N}}. \]  \hspace{1cm} (A1)

Here, it is transformed as follows:

\[ N = ML, \quad k = k_1M + k_0, \quad n = n_1L + n_0, \]  \hspace{1cm} (A2)

\[ F(k_1M + k_0) = \sum_{n_0}^{L} \left[ \sum_{n_1}^{M} f(n_1L + n_0)e^{-j \frac{2\pi n_1k_0}{M}} e^{-j \frac{2\pi n_0k_1}{M}} \right] e^{-j \frac{2\pi n_0k_0}{N}}. \]  

This equation is renewed more as follows:

\[ F'(n_0, k_0) = \sum_{n_1}^{M} f(n_1L + n_0)e^{-j \frac{2\pi n_1k_0}{M}}, \]  \hspace{1cm} (A3)

\[ F''(n_0, k_0) = F'(n_0, k_0)e^{-j \frac{2\pi n_0k_0}{N}}, \]

\[ F(k_1M + k_0) = \sum_{n_0}^{L} F''(n_0, k_0)e^{-j \frac{2\pi n_0k_1}{N}}. \]

References


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