Design of the Deep Space Interferometry Digital Backend

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The deep space interferometry digital backend plays an important role in the deep space VLBI (Very Long Baseline Interferometry) station, whose performance determines the angular measurement precision. This paper describes a design and implementation of a deep space interferometry digital backend and mainly researches some key technologies in the recording sub-system. Compared to traditional systems, the backend integrates the function of VLBI DBBC (Digital Base Band Converter) and VLBI recording system. Depending on the high-performance and flexible hardware platform, the recording sub-system is VSI-H (VLBI standard Interface - Hardware) compliant and supports real-time e-VLBI transmission. For exchanging VLBI raw data with other international space agencies conveniently, both Mark 5B data format and Delta-DOR RDEF (Raw Data Exchange Format) are supported. Based on the standard computer system and disk array, multi data transmission and recording modes are supported. The recording speed is up to 1600Mbps and the storage capacity can be expanded as needed. Based on Windows OS and primarily on unmodified COTS (Commercial Off the Shelf) technology, the development and maintenance of the system is very easy.

I. Introduction

DELTA-DOR is a Very Long Baseline Interferometry (VLBI) technology that is becoming a standard part of the deep space navigation mission. By observing the spacecraft and a quasar that is close in an angular sense to the spacecraft alternately, the effects of public errors such as transmission media delays, Earth orientation and station locations are diminished, Delta-DOR can be used in conjunction with Doppler and ranging data to improve spacecraft navigation by more efficiently determining spacecraft angular position in deep space[1].

The structure and signal processing flow of Delta-DOR is shown in Figure 1. Radio frequency (RF) signals from the spacecraft or the quasar are converted to broadband IF signal by the radio receiver. Baseband converter processes the selected frequency band and yields channelized baseband signals according to the observation mission. When observing the spacecraft, due to the high signal-to-noise ratio (SNR), the baseband converter yields narrow bandwidth data with high sample-bit. When observing the quasar, due to the low SNR, the baseband converter yields wide bandwidth data with low sample-bit. Formatter collects selected sub-channel data in sequence and adds ancillary information such as time tag to the data stream according to the format specification. Data recorder stores the formatted data into the storage media. Record data can be sent to a remote data correlation center in real time through the network or after the mission through the network or disk transportation. The formatted data from two stations are correlated and processed, and the precise angular position of spacecraft is generated.

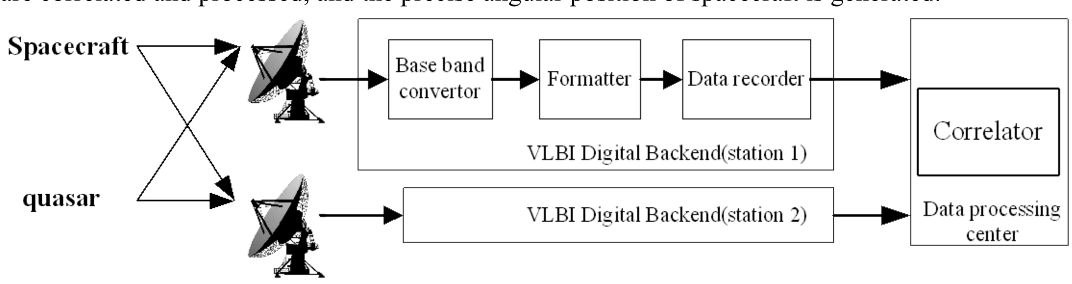

Figure 1. The structure and signal processing flow of Delta-DOR

The digital backend system (DBE) consists of baseband converter, formatter and data recorder, performs all the signal processing functionalities between the RF receivers and data correlation center. As a high-precision measurement technology, the performance of DBE determines the observation capabilities of Delta-DOR to a large extent. With the rapid development of technology and higher levels of science objectives, the design of new DBE should take following items into consideration[2]:

1) Definition of a new system to be used as backend, than performing all the signal processing functionalities included between the receivers output and the data transmission or recording;
2) Digital implementation of the entire set of functionalities included in the point above, today performed partially in the digital and in part in the analog domain;
3) Important improvement of reliability and technical performance, for getting improved data quality;
4) Cost reduction with respect to the traditional terminal, for a possible broad usage;
5) Flexibility in terms of functionality and upgrading possibility;
6) VLBI Standard Interface(VSI) to ensure good connection with other VSI-compliant instruments;
7) Standard format, for exchanging VLBI raw data among space agencies conveniently;
8) E-VLBI transportation and disk-based recorder to improve the reliability and performance of data transportation and recording.

In this paper, we present the design scheme of the deep space interferometry digital backend system. Depending on the high-performance and flexible hardware platform, the DBE integrates the functionalities of Digital Base Band Converter (DBBC), multi-modes formatter and disk-based recorder. Based on Windows operating system and primarily on unmodified Commercial Off the Shelf (COTS) technology, the maintenance and upgrading of the system is very easy. We present the design scheme of the deep space interferometry digital backend system. Details of the hardware configuration are stated in section II. Main functions are given in section III. Section IV summarizes this paper.

II. Hardware configuration

A. Overall structure

The system consists of an analog signal pre-processing board, a signal acquisition and processing board, a data interface board, a universal CPCI industry computer and a disk array. The block diagram of deep space interferometry digital backend system is shown in Figure 2.

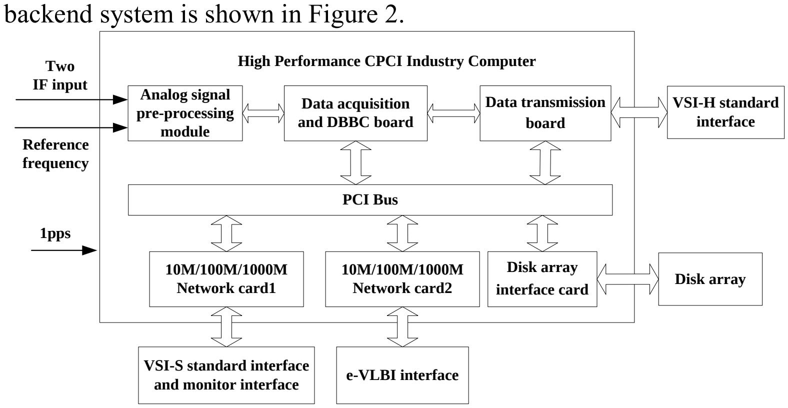

Figure 2. Deep space interferometry digital backend system configuration

The analog signal pre-processing board receivers the two IF analog signals and performs the pre-processing including AGC control, low pass filter, etc; The signal acquisition and processing board provides high-performance software-defined radio platform which is the key part of the system, details of its hardware configuration are described in section B; The data interface board has a VSI output port and ensure good connection with other VSI-compliant instruments ,such as MARK 5B[3]; The universal CPCI industry computer provides reliable and flexible architecture and is conducive to adopt Commercial Off The Shelf (COTS) products and build a powerful platform rapidly, what's more, the computer has a disk array interface card and two 10M/100M/1000M Ethernet ports. The disk array interface card is used to record and replay the baseband data in conjunction with the disk array. The two Ethernet ports can be used as e-VLBI [4]interface, VSI-S [5]interface and monitor interface.

B. Key board

The signal acquisition and processing board is the key board of the system and designed as a high-performance software-defined radio platform. It consists of data acquisition unit, data monitor unit, signal processing unit, data formatting unit , PCI bus control unit, high-speed buffer unit, clock management unit. The block diagram of the signal acquisition and processing board is shown in Figure 3.

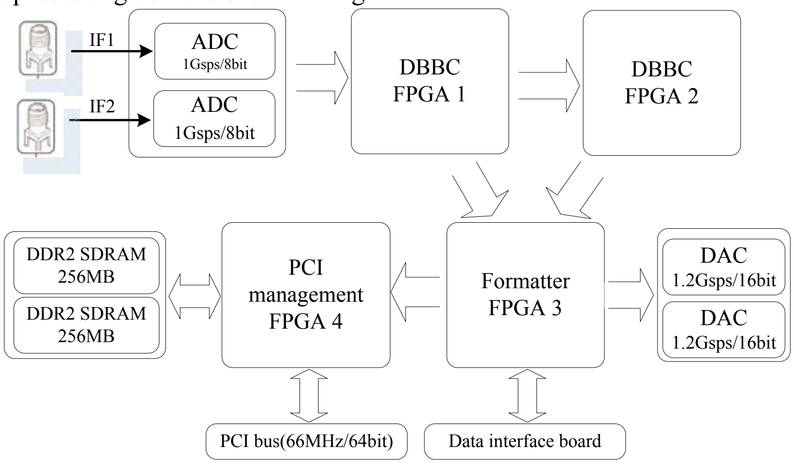

Figure 3. Signal acquisition and processing board configuration

The data acquisition unit has two ADC with dual-channel 1Gsps and 8bit resolution. The ADC can be used as a single-channel 2Gsps ADC. The data monitor unit has two DAC with dual-channel 1.2Gsps and 16bit resolution. Signal processing unit has two powerful FPGA, can afford the huge resource consumption of DBBC. Data formatting unit use a FPGA same as signal processing unit to perform the data formatting under multiple mode and it can also sent the raw baseband data directly to the data interface board. PCI bus control unit is responsible for handling all PCI transactions, provides flexible and convenient means to control and monitor the board. High-speed buffer unit has two DDR2 SDRAM with 512MByte. Clock management unit uses 1PPS and 10MHz reference frequency signals and clock PLL to generate a variety of clocks including the synchronous sampling clock. FPGA1, FPGA2 and FPGA3 can be dynamically reconfigured through PCI bus and that is a feature of this board which can optimize the architecture to the needed performance and satisfy the present and a reasonable future necessity.

III. Main functions

A. DBBC Sub-system

The DBBC subsystem can process two IF analog signals with 512MHz bandwidth and output at most 16 channel baseband signals with bandwidth from 16MHz to 1kHz and quantization bits 2-16 bits selectable. DBBC sub-system is mainly composed of analog signal conditioning module and data acquisition and baseband conversion board. The sub-system has two working modes. One is real baseband output mode, the other is complex baseband output mode. Each mode has different signal processing algorithm and data frame format. Mark5B format is adopted for real baseband output mode and REDF (Delta-DOR Raw Data Exchange Format) format for complex baseband output mode.

Each IF analog signal is AGC controlled and filtered to limit its bandwidth to the range of 512MHz, then digitized at 1024MHz with 8-bit resolution. The digitized data are fed to baseband conversion units. For real data stream output, the algorithm combined effective uniform channelization with orthogonal mixing[6] is adopted (Figure 4). For complex data stream output, the algorithm based on multi-channel parallel NCO orthogonal mixing in conjunction with polyphase filter is adopted (Figure 5). Both modes can perform full spectrum processing of received signal. The maximum output data stream of DBBC sub-system is 16 channels, with bandwidth 1kHz-16MHz and re-quantization 1, 2, 4, 8, 16 bit selectable.

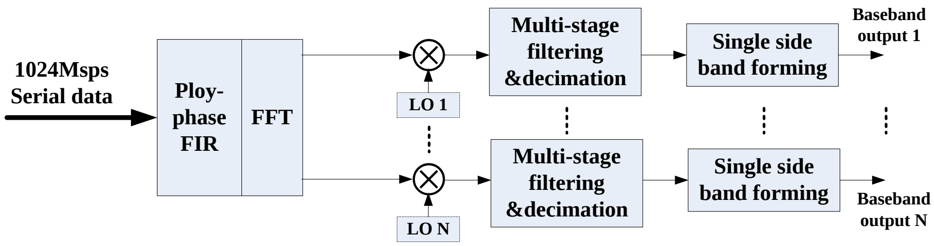

Figure 4. Block diagram of real data stream output scheme

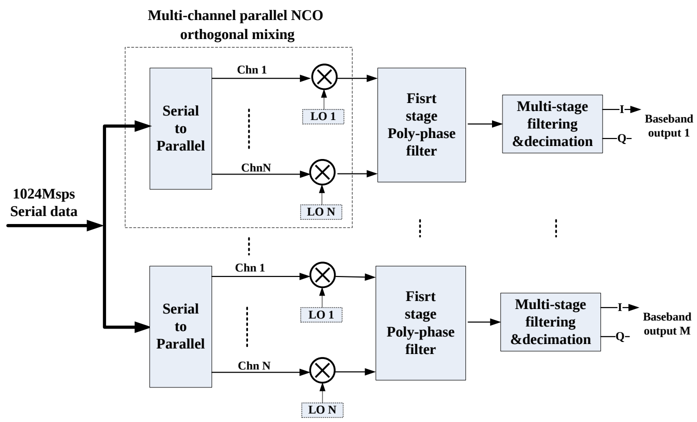

Figure 5. Block diagram of complex data stream output scheme

B. Date formatting

When performing a Delta-DOR measurement involving two (or more) agencies, raw baseband data must be exchanged at least between one of the agencies that has acquired the data and the agency that runs the correlation process and provides the results. The need of the raw data exchange intrinsically comes with the characteristics of the measurement that, being an interferometric technique, calls for the correlation of at least two data streams simultaneously acquired. It is believed that using standard raw data format among different agencies will reduce development and operations costs while improving navigation capabilities by increasing the number of intercontinental ground station baselines.

In order to strengthen international cooperation, the system supports two data format. One is Mark 5B data format, corresponding to VLBI mode. The other is RDEF[7] format, corresponding to Delta-DOR mode. The difference of the two format is shown in table 1.

Table 1. Comparison between Mark 5B format and RDEF format

	Mark 5B format	RDEF format
file type	one record file made of header section and data section with all channel recorded data	one observation file made of a sequence of ASCII text lines and multiple product files made of header section and data section with single channel recorded data
data type	real	complex
header section	16 Byte	176 Byte(product file)
data section	fixed 2500*4 Byte	one second of data, the length is variable and determined by the sample rate and sample size of the recorded data.
sub-channel sampling bit	Every data frame contains the data of all sub-channels. the sub-channel sampling bit is 1, 2, 4 or 8-bit and the sum of all channel sampling bit must be 1, 2, 4, 8, 16 or 32-bit	Every data frame contains the in-phase (I) and quadrature-phase (Q) samples of only one sub-channel. the Q data or the I data sampling bit is 1, 2, 4, 8 or 16-bit

It can be seen that Mark 5B format is relatively simple but not flexible. RDEF format contains more information about the Delta-DOR measurement and a separate product file is created for each subchannel. This is especially useful for software correlator.

C. Data transmission and recording

This system uses the platform of the CPCI industry computer which is conducive to build a flexible and reliable system and the data transmission and recording shall not rely on dedicated hardware platforms and operating system.

In order to facilitate international cooperation with other agencies and adapt to the development of the VLBI technique, the data transmission and recording has a total of six operating modes, shown in Figure 6.

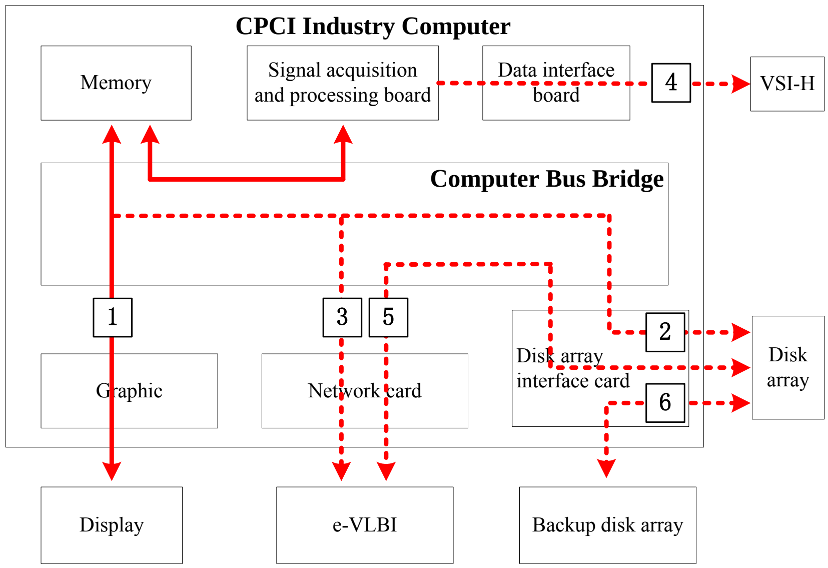

Figure 6. The schematic diagram of the data transmission and recording

1) Preview mode, refers to the preview of the baseband data on each sub-channel in time domain or frequency domain, monitor the status of each sub-channel and modify the sub-channel parameters and AGC control. Shown the path 1 in Figure 6, the IF signals are processed by DBBC and formatter in signal acquisition and processing board, then sent to the computer's memory through the PCI bus. Every second, the software application will acquire an amount of data, remove the header section and display the interesting information;
2) Recording mode, refers to store the baseband data in the disk array. Shown the path 2 in Figure 6, the baseband data in the memory is stored in disk array through the disk array interface card;
3) Real-time e-VLBI mode, refers to sent the baseband data to the data processing center by real-time e-VLBI. Shown the path 3 in Figure 6, according to the TCP protocol, the baseband data transmitted to the memory is transmitting to external through the 1000M Ethernet port directly.
4) Mark 5B mode, refers to store the baseband data in the Mark 5B recorder directly. Shown the path 4 in Figure 6, the baseband signal after the DBBC is sent to the data interface board directly, and recorded in Mark 5B recorder through the VSI-H interface;
5) Post e-VLBI mode, refers to that the system exchanges with other instruments by network after the mission. Shown the path 5 in Figure 6, using the FTP protocol, the record files in disk array are transmit to external such as data processing center through the disk array interface card, computer bus and network card. In addition, the disk array can also receive the record files;
6) Backup mode, refers to backup the record files to a small disk array. Shown the path 6 in Figure 6, record files in the disk array can be copied via the USB port or SATA interface to the backup hard disk.

In the above modes, the Recording mode, Real-time e-VLBI mode and Mark 5B mode is independent. They can work alone or simultaneously, and monitor the signal through the software application.

Sustained and high-speed data recording is a key technology in this system. In order to ensure that the data can't be miss or wrong, the real-time requirements of the system must be taken into consideration. As the computer is not a real-time data transmission equipment, and the speed of data transmission fluctuates enormously, while the speed of baseband data stream is sustained. So two high-speed DDR2 SDRAM are used to achieve the matching of the speed, the cache capacity is up to 512MByte. When recording, the computer memory is used as a cache and the high-speed raw data is transmitted from the signal acquisition and processing board to the disk array. Because the DMA transmission and the disk recording cannot go simultaneously, the multi-threading technology must be used and the speed of disk recording must be high enough. Taking into account for minimizing the impact of the operating system and file conversion, the method of operating with whole sector on the disk is used and the sustaining recording and playback speed is improved efficiently. Through those efforts and test, the sustaining recording and playback speed between the signal acquisition and processing board and the disk array is up to 1600Mbps.

IV. Conclusion

This paper introduces a design and implementation of a deep space interferometry digital backend. The DBE integrates the function of baseband data conversion, data formatting and data transmission and recording, can provide at most 16 channel baseband outputs with bandwidth from 16MHz to 1kHz and quantization bits 2-16 bits selectable. Both Mark 5B and REDF data format are supported for international cooperation. Five data transmission and recording modes are implemented in system to meet different requirement in international cooperation with other agencies. System structure is configured with removable hard disk array and features modularization and optional COTS input and output boards based CPCI specification. The sustaining recording and playback speed between the signal acquisition and processing board and the disk array is up to 1600Mbps.

Appendix A
Acronym List

VLBI	Very Long Baseline Interferometry
VSI	VLBI Standard Interface
CPCI	Compact Peripheral Component Interconnect
DOR	Differential One-way Ranging
RF	Radio Frequency
IF	Intermediate Frequency
DBE	Digital Backend System
DBBC	Digital BaseBand Converter
COTS	Commercial Off the Shelf
REDF	Delta-DOR Raw Data Exchange Format

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