Development of a new seismic-data acquisition station based on system-on-a-programmable-chip technology

Zhang Qi-sheng[1,4], Deng Ming[1,4,*], Guo Jian[2,3], Luo Wei-bing[3], Wang Qi[1], Feng Yong-qiang[1]

[1] *China University of Geosciences, Beijing, China*

[2] *Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China*

[3] *Beijing Geophysics Technology Co. Ltd., Beijing, China*

[4] *Key Laboratory of Geo-Detection, China University of Geosciences, Beijing, and Ministry of Education, Beijing, China*

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ABSTRACT

There has been considerable development of seismic detectors over the last 80 years. However, there is still a need to further develop new earthquake exploration and data acquisition systems with high precision. In particular, for China to keep up with the latest technology of these systems, it is important to be involved in the research and development, instead of importing systems that soon fall behind the latest technology. In this study, the features of system-on-a-programmable-chip (SoPC) technology are analyzed and used to design a new digital seismic-data acquisition station. The hardware circuit of the station was developed, and the analog board and the main control data-transmission board were designed according to the needs of digital seismic-data acquisition stations. High-definition analog-to-digital converter sequential digital filter technology of the station (cascade integrator comb filter, finite impulse response digital filter) were incorporated to provide advantages to the acquisition station, such as high definition, large dynamic scope, and low noise. A specific data-transmission protocol was designed for the station, which ensured a transmission speed of 16 Mbps along a 55-m wire with low power consumption. Synchronic acquisition was researched and developed, so as to achieve accuracy better than 200 ns. The key technologies were integrated into the SoPC of the main control data-transmission board, so as to ensure high-resolution acquisition of the station, while improving the accuracy of the synchronic acquisition and data-transmission speed, lowering the power consumption, and preparing for the follow-up efforts to tape out.

1. Introduction

In over the last 80 years, the development of seismic exploration instruments has gone through five stages: the electron tube (optical spot recorders), transistors (analog tape recorders), conventional digital seismographs (digital tape recorders), 16-bit telemetry seismography, and 24-bit telemetry seismography [Song et al. 2012]. At the beginning of the 21st century, ION and Sercel launched the IV system and the 400 series of fully digital seismographs, respectively, which were recognized in the industry as sixth generation seismographs [Song et al. 2012]. The development of seismic instruments cannot be separated from the continuous development of seismic-data acquisition methods, combined with the latest technology available at the time. Currently, seismograph development is closely related to and mutually reinforces the progress of electronic technology, computer science, seismic exploration methods, intelligent control, network technology, signal processing, and other disciplines.

As early as the 1970s, Sercel in France launched the SN338 digital seismograph with its single-station, single-channel, data-acquisition station [Huang and Yu 1994]. At present, the most advanced seismic field-data acquisition systems internationally are multi-channel seismographs, which are mainly represented by: the fully digital platform of System Four (upgraded in 2007 to Scorpion), with the FireFly acquisition system, launched by ION in the USA; the 428XL acquisition system of Sercel in France; and ARAM ARIES of GEO-X in Canada. The maximum number of channels of the input/ output System Four has reached 30,000, and it can be used in conjunction with multi-component digital detectors, to achieve full-wave seismic-data acquisition. A cable-less connection for this was achieved with FireFly, which significantly reduces the transportation costs in the field. Then the 428XL has a real-time channel capacity of up to 100,000, thus guaranteeing the highest resolution data while having more channels. From these data, it can be speculated that seismographs designed outside of China have reached a high level of channel capacity and connection patterns, and are advancing towards high-resolution, high-density seismographs with more diversified connection patterns.

From a global perspective, 50% dependence on foreign oil can be seen as a security warning, but in 2011, China's dependence on foreign oil exceeded 55%, which is a threat to energy and economic security [Mazza et al. 2012, Qi 2012]. Therefore, China should strengthen domestic oil and gas resource prospecting to contribute to national stability, sustainable development, and building of a more prosperous society. The most widely used and powerful geophysical method in oil and gas exploration is reflection seismology [Wood and Gettrust 2002, Morandi and Ceragioli 2002]. As oil and gas exploration techniques have developed, China has entered a very difficult stage of oil and gas exploration; namely, exploration of the pre-Cenozoic marine residual basins [Wu et al. 2011]. This will require oil and gas resources to be sought in complex geological areas, such as buried hills and their internal structures, and high and steep structures on mountainsides. Not only will exploration depth increase, but surface and subsurface conditions will also become more complex, and hence seismographs will face new demands and challenges. There is thus an urgent need to develop new types of high-precision seismic-data acquisition systems that are suitable for our national conditions.

In recent years, with national attention being placed on research and development of geophysical instruments, the number of research units engaged in seismic-data acquisition and recording systems has grown. BGP Inc. of the China National Petroleum Corporation (Group) and Tsinghua University have developed the 'ES109 new seismic-data acquisition and recording system', with a capacity of 2,000 channels in a single tape track, and a total channel capacity of 20,000 [Wang 2010]. The Institute of Geology and Geophysics of the Chinese Academy of Sciences has designed a new digital seismograph and a sea seismograph with broadband and double cabins, which have low cost and low power consumption, yet are still very powerful and can achieve 10,000-channel data transmission using reliable methods. Jilin University used an ethernet relay solution to achieve a single station 8-channel seismic-data acquisition and recording system, with a transmission distance of 100 m, and a transfer rate of 16 Mbps. This has now passed the indoor tests and seismic focus experiments [Zhang 2007]. The University of Science and Technology of China has adopted long-distance ethernet physical layer technology and has customized transfer protocol programs to achieve a peak transfer rate of 40 Mbps [Xie 2009]. The Chengdu University of Technology has achieved wireless telemetry with a 48-channel, high-resolution, shallow-layer, digital seismograph based on wireless communication technology, which has enhanced seismograph construction capacity in mountain and foothill areas. In recent years, although China's research and development capabilities for seismic exploration instruments have been increasing, the vicious cycle of 'import - fall behind - import again - fall further behind' over 30 years of economic reform has created a wide gap in the research and production of digital seismic-data acquisition systems in China, compared to that in more developed countries. The achievement of high-resolution, high-precision, synchronized data-acquisition and real-time high-speed data transmission at low power (less than 200 mW for each station) is still the aim of seismograph developers. Therefore, there is a very important practical significance in the study of the key technologies of digital seismic-data acquisition stations, and in the development of such a station for which China owns the independent intellectual property rights.

2. System-on-a-programmable-chip technology and telemetric digital seismic-data acquisition stations

The nature of telemetric digital seismic-data acquisition stations led to the introduction of system-on-a-programmable-chip (SoPC) technology. In turn, the advantages of SoPC have greatly enhanced the performance of telemetric digital seismic-data acquisition stations.

2.1. System-on-a-programmable-chip technology

SoPC technology was first proposed by Altera Corporation in the USA in 2000, together with the corresponding development software, Quartus II. SoPC is a system on a chip that is based on field programmable gate array (FPGA) solutions, which integrates the processor, memory, input/ output ports, low-voltage differential signaling, clock and data recovery, and other components, as well as other functional modules required by the users of a programmable logic device, to construct a programmable chip system [Astarloa et al. 2005, Zhang et al. 2012]. It has a flexible design that can be trimmed, is scalable and upgradeable, and has hardware and software system programmability [Zhang et al. 2012]. SoPC is an integration of programmable logic-device technology and application-specific integrated circuit technology, which represents the direction of future development in the semiconductor industry. This is because it has the advantages of being a single chip with micro-encapsulation, low-power consumption, and high programmability, and it is easy to develop and tape-out. Therefore, with the development

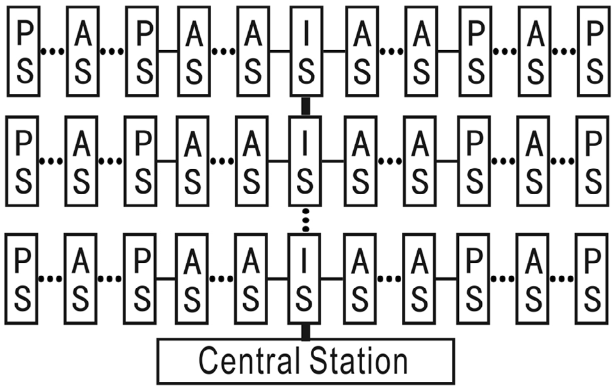

Figure 1. Block diagram of a telemetric digital seismic instrument. PS, power station; AS, acquisition station; IS, interconnection station.

of electronic design automation technology and the continuous improvement of large-scale programmable devices, SoPC technology has already been widely used in many fields [Zhang et al. 2012]. In the present study, SoPC technology was used to design a new digital seismic-data acquisition station. The details of the key technologies involved in designing the telemetric digital seismic-data acquisition station based on SoPC are explained thoroughly here.

2.2. Components of telemetric digital seismographs

Telemetric digital seismographs are composed of the detector, data-acquisition stations, power stations, interconnected stations, and a central station (instrument cart) [Zhang et al. 2012]. The system structure is shown in Figure 1. There are high-speed fiber-optic connections between individual interconnected stations, as well as between these stations and the central station. Special four-core cables for seismic exploration are used for the connection between the power station and the acquisition station. The detector and the acquisition station together constitute the front end of the acquisition device, while the interconnected stations and power station provide the power-over-ethernet mode of power supply to the connected data-acquisition station. These also serve as relay devices for data collection, to achieve high-speed, high-fidelity uploading for bulk data, while the central station is responsible for monitoring the work of the entire acquisition system.

2.3. Overall framework of a new telemetric digital seismic-data acquisition station based on system-on-a-programmable-chip technology

Data-acquisition stations are one of the most basic components of a telemetric digital seismograph. The overall framework of the data-acquisition station used in the present study is shown in Figure 2. CS5373 plus SoPC are used to achieve high-precision conversion and high-speed digital transmission. The earthquake input signal bandwidth is 2 kHz DC. A Nios processor generates commands, and an analog-to-digital converter (ADC) controller controls the CS5373 to perform the analog-to-digital conversion, thereby generating a serial data stream at 512 kbps. The sigma-delta (Σ-Δ) serial datastream has a low sampling accuracy and a large sampling rate. To improve accuracy, high-resolution ADC digital filtering techniques must be introduced. After passing through a Σ-Δ converter, a cascade integrator comb (CIC) filter (designed by the authors of the present study) is used for low-pass filtering for the Σ-Δ serial datastream. After the data has passed through the CIC filter, the data rate is reduced, but the quantified noise spectral density remains unchanged after sampling. After this, finite impulse response (FIR) digital filtering, infinite impulse response (IIR) digital filtering, and high-precision synchronization are carried out, and the data are transmitted to the power station using the

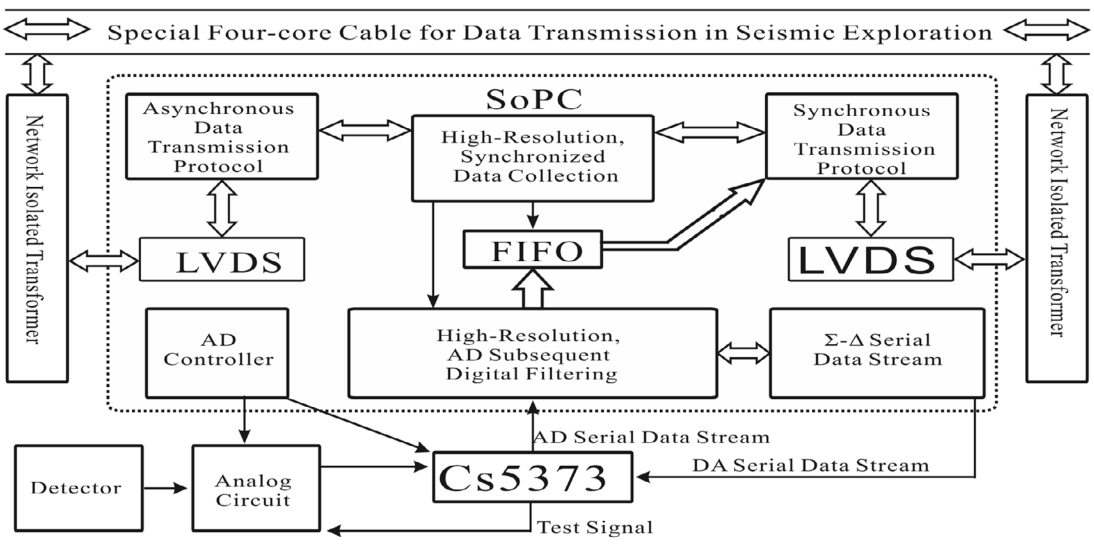

Figure 2. The overall structure of the data-acquisition station with the CS5373 subsequent digital filter, which was independently designed.

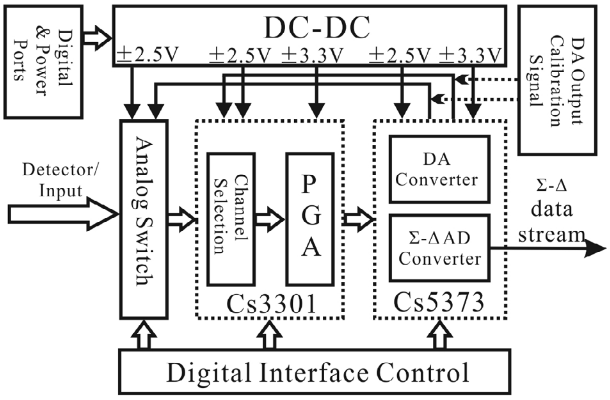

Figure 3. Block diagram of the analog board of the data-acquisition station.

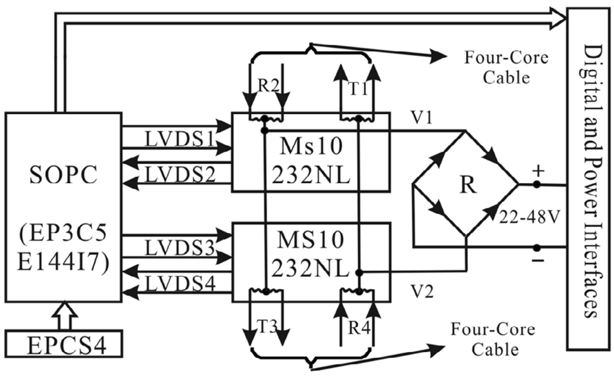

Figure 4. Block diagram of the master data-transmission board.

low-voltage differential signaling data-transmission module. The data-acquisition station that we developed has the following features: (1) high-resolution analog-to-digital conversion, and subsequent CIC, FIR, and IIR digital filters, which are suitable for geophysical data acquisition; and (2) data-acquisition station core technology integrated into a single-chip SoPC. After industrialization, this can easily be customized into a monolithic integrated chip, for which independent intellectual property rights can be obtained. Power consumption after customization can be further reduced, while the performance and integration can also be improved.

3. Key technologies of the new telemetric digital seismic-data acquisition station

3.1. Hardware circuit design of the data-acquisition station

The hardware circuit of the data-acquisition station based on SoPC consists of two stacked circuit boards: (1) an analog board is used for the acquisition of seismic-wave data received by the detector, after which analog signal conditioning, high-precision analog-to-digital conversion, and direct-current-to-direct-current (DC-DC) conversion are carried out, and (2) a master data-transmission board is used to control the modules in every unit on the analog board and the transmission of the data flow.

The analog board block diagram of the data-acquisition station is shown in Figure 3. The analog switch used an ADG733 chip, with the signals selected by the detector or the calibration signals from the CS5373 passed through the passive filter module, and then through the CS3301 programmable gain differential amplifier for programmable magnification (the magnification can be set to 1, 2, 4, 8, 16, 32 or 64 times). Finally, the signal is sent to the CS5373 high-precision Σ-Δ ADC to be digitized. As the power station in the telemetric digital seismic-data acquisition station design supplies power in power-over-ethernet mode, when the power station supplies power to multiple data-acquisition stations, the voltage from the power station steadily decreases. Depending on the location of the data-acquisition station, its voltage varies from 22 V to 48 V, while the data-acquisition station analog board needs ±2.5 V and 3.3 V. The PWB4803MD type DC-DC chips convert the input voltage to 3.3 V, after which the LT1161 and LT1962 convert the 3.3 V to -2.5 V and +2.5 V, as required.

The master data-transmission board block diagram is shown in Figure 4. It consists primarily of the EP3C5E144I7 SoPC chip and the EPCS4 configuration chip. As for data transmission, four pairs of low-voltage differential signaling interface cables and two MS10232NL network-isolation transformers are used. The R2 and T1 are used as a pair of transceivers, while the R4 and T3 are used as another pair of transceivers. The intermediate taps of (R2, T3) and (T1, R4) are extracted, and have common-mode voltage, V1 and V2. The power station uses power-over-ethernet mode power supply, such that the common-mode voltage difference between V1 and V2 is 22 V to 48 V, which is related to the position of the data-acquisition station. It passes through the bridge rectifier circuit, R, to identify the positive and negative voltage, and it is then sent to the analog board for DC-DC conversion. The analog board and the master digital transmission board have digital and power interfaces for docking, to provide the information exchange and the power supply.

3.2. Digital filtering techniques of the high-resolution analog-to-digital converter

The high-resolution digital-filtering technology of the ADC is one of the difficulties encountered when designing telemetric seismic-data acquisition stations. The flow chart of the design of the filter implementation is shown in Figure 5. It is used mainly to complete the sampling filtering for the 1-bit Σ-Δ stream from the

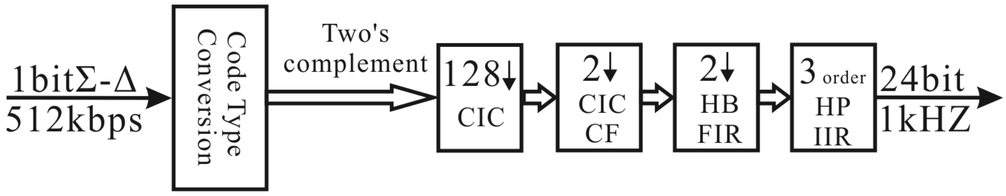

Figure 5. Acquisition of high-definition AD transmission digital filter by the data-acquisition station. HB FIR, half-band FIR filter; CF, compensation filter; HP IIR, high-pass IIR filter.

CS5373 modulator, and to improve the resolution while reducing the sampling rate. Geophone signals after CS5373 modulation have an output of 512 kbps bit *Σ-Δ* stream. As the input and output of the CIC filtering use two's-complement, conversion modules are used to convert this into binary two's complement (0 is converted to 11, 1 is converted to 01). The binary two's complement is then passed through the fifth-order CIC filter (as the decimation rate of the CIC is 128, the sampling rate of the CIC output is 4 kHz), the CIC compensation filter (as the decimation rate of this CIC is 2, the sampling rate is 2 kHz), the half-band FIR filter (the decimation rate of the FIR is 2) and the third-order IIR high-pass filter. Finally, 24-bit output data with a sampling rate of 1 kHz are sent to the first-in, first-out buffer of the SoPC.

$$H(z) = \left[\frac{1 - z^{-128}}{1 - z^{-1}}\right]^5 \tag{1}$$

$$h(n) = \begin{cases} 1, & 0 \le n \le 127 \\ 0, & n > 127 \text{ or } n < 0 \end{cases} \tag{2}$$

The transfer function of the fifth-order CIC filter design is shown in Eq. (1). It can be seen from Equation (1) that it is a five-cascade CIC decimation filter, and that the single-stage CIC filter might be a concatenation of the integrator and a comb-like device. The single-stage filter impulse response is shown in Equation (2), which demonstrates that the single-stage CIC filter can be achieved using a memory unit and an adder, without a multiplier. This provides a significant saving of logical resources within the SoPC (FPGA). As the fifth-order CIC filter has a certain degree of attenuation within its pass band, it needs a CIC compensation filter for pass-band compensation.

After passing through the CIC decimation filter and the compensation filter, the data still need double down-sampling, which can be realized through a half-band FIR filter. The half-band FIR is a symmetric FIR, with an intermediate design factor of 0.5, and the coefficients of the other odd terms of 0. Owing to the symmetry of the coefficients, the actual nonzero coefficients are only a quarter of the total filtering coefficients, which greatly decreases the logical resources and power consumption within the SoPC (FPGA). To filter out DC and low-frequency signals, at the final level of the high-resolution ADC of the data-acquisition station, a 0.3% fs, third-order high-pass IIR filter was designed.

3.3. The dedicated data-transmission protocol of the data-acquisition station

To achieve reliable, high-speed data transmission for the data-acquisition station, a dedicated data-transmission protocol based on the characteristics of the seismic-data acquisition has to be designed. This mainly involves two problems: encoding of the data transmission between the data-acquisition stations, and design of the data-frame protocol.

Manchester coding is used for data-transmission encoding, where a synchronization clock can be extracted from the signal to reduce the peripheral circuit design and power consumption. In addition, glitches that occur easily in data edges when using conventional encoding can be avoided. The FPGA coding module converts 8-bit parallel data into 16.384 Mbps serial data through the Manchester coding. The decoding program uses the oversampling approach, with a sampling frequency 8-times that of the data transmission, to detect whether data transitions occur within the effective transition time, and then to complete data sampling, decoding, data shift, synchronization code determination, and byte synchronization.

After Manchester decoding, serial binary data can be transmitted. However, to effectively transmit data, the problems of frame synchronization and byte synchronization must also be solved. At the receiving end, upon receipt of the preamble code 01011111, one frame of data reception begins. The first part of this frame is the header data, which contains the data length of this frame. The receiving end then receives the data in accordance with the data length defined in the header, and then restores the data into parallel data in units of bytes.

In the data-frame protocol design, the characteristics of seismic-data acquisition are combined, and the data frame is divided into 51 units; as there are 816 bytes, each unit contains 16 bytes (as shown in Table 1), within which there are the unit header, command, status, and cyclic redundancy check code as one byte each, whereby the data comprise 12 bytes. The first unit is the header segment, where the header data includes the data length of the frame, and the other 50 units are data units used

Unit header	Command	Status	Data	CRC
1 byte	1 byte	1 byte	12 bytes	1 byte

Table 1. Cell format of data frames in an acquisition station. CRC, cyclic redundancy check code.

for communication between the power stations or between a power station and a data-acquisition station.

The relay synchronous acquisition and asynchronous communication of the data-acquisition station are shown in Figure 6. The seismic-data acquisition station has its own data transmission characteristics. It uses synchronous acquisition for the main power station to send commands to the data-acquisition station, for the secondary power stations to send commands, and for the data and status information of the data-acquisition station to be uploaded to the secondary power station; however, it uses asynchronous transmission for sending data and status information from the secondary power station to the main power station.

In synchronous acquisition, the main power station sends out ready-made null-data frames with no data acquisition, and each data-acquisition station performs the appropriate action according to the command in the data frame, or writes four 24-bit sample data into the corresponding cell during the acquisition period, sets the unit status word to 1, sets the command byte to 0x0F, and finally re-calculates and writes the unit cyclic redundancy check code. In the asynchronous transmission direction, no change is needed for the data frame, and it only re-encodes the data received and sends them out; in this direction, the acquisition station is only a relay between the power stations, and the data frames can pass through quickly.

3.4. High-precision synchronous data acquisition

Synchronous data acquisition implies that all of the data-acquisition stations will collect data from each detector at the same time, and will transmit the collected data completely and systematically to the cable acquisition unit (power station), and that the synchronization accuracy is one of the main performance indicators of the seismograph. The main and secondary power stations send out synchronous data-acquisition commands to control the collection station to achieve

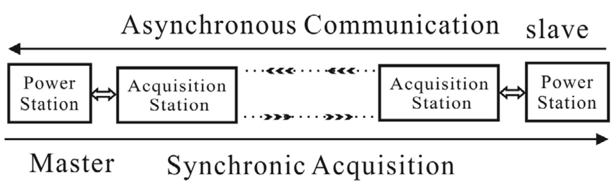

Figure 6. Schematic diagram of synchronous data-acquisition and asynchronous communication of the data-acquisition station.

high-precision synchronous data acquisition. When the collection station receives data from the main power station by synchronous data acquisition, it decodes the data frame. If it is a synchronous data-acquisition command frame, time is counted while it is transmitting the data frame to the next data-acquisition station, until the data-acquisition station receives the synchronous acquisition command frame sent from the power station in asynchronous communication mode.

If at the n^{th} collection station, the time counted is T_n, then:

$$T_n = A_n + S_n + T_S \tag{3}$$

$$P_n = S_n - A_n \tag{4}$$

$$P_n + T_n = 2S_n + T_s \tag{5}$$

$$S_n = \frac{1}{2}(P_n + T_n - T_S) \tag{6}$$

where the time used in the synchronous data-acquisition command frame in the synchronous data-acquisition mode is S_n; the time used in the asynchronous transmission mode is A_n; the time used for re-transmission from the power station is T_s; and the time difference between the synchronous data-acquisition and asynchronous transmission is P_n. In the process of synchronous acquisition and asynchronous transmission, the transmission times consumed in the cable are almost identical; therefore, P_n can be regarded as the processing time difference between the different transmission modes of the data-acquisition station. If for the i^{th} synchronous data-acquisition station, the processing time is t_i, and for asynchronous transmission, the processing time is t_i', when there are m data-acquisition stations,

$$P_n = \sum_{i=n+1}^{m} (t_i - t_i') \tag{7}$$

$$S_n = \frac{1}{2}\left(\sum_{i=n+1}^{m} (t_i - t_i') + T_n - T_S\right) \tag{8}$$

where t_i, t_i' and T_S can all be obtained through actual measurements, and a list can be established for each data-acquisition station. Therefore, in the future, when the acquisition command frame is received, S_n can be delayed to achieve synchronous data acquisition. Previously, all of the acquisition times of the data-acquisition station were the moment when they received the synchronous acquisition command frame from the power station.

For hardware circuit testing, two power stations with 15 data-acquisition stations were used, and the distances between the data-acquisition stations were 25 m to 55 m. The synchronization accuracy between the data-acquisition stations was always better than 200 ns.

4. Collection station performance indicators

Following tests and analyses in the laboratory and the field, the data-acquisition station developed has the following performance indicators:

(1) Full-scale input: better than 1.6 V RMS at 0 dB and 25 mV RMS at 36 dB;
(2) Acquisition station power consumption: 260 mW
(3) Acquisition station interval: up to 55 m;
(4) High-pass filtering: 3 Hz;
(5) Low-pass filtering: 0.8 FN (digital filter);
(6) Sampling rate: 1 kHz;
(7) Word length: 24 bits;
(8) Power supply: DC 18-72 V, long-distance supply with signal transmission cable;
(9) Dynamic range: 120 dB at 0.4 kHz BW (1 kHz sampling rate);
(10) Self-harmonic distortion: -105 dB;
(11) CMRR: > 102 dB;
(12) Stop-band attenuation > 120 dB (above the Nyquist frequency);
(13) Noise (3-200 Hz): 450 nV RMS at 0 dB;
(14) Data-transmission speed: 16 Mbps;
(15) Synchronization accuracy: better than 200 ns;
(16) Operating temperature: −20 °C to +70 °C.

5. Conclusions and discussion

In the present study, a new type of digital seismic-data acquisition station was designed, based on the SoPC technique. Through the research and development program, the following technical aspects were explored:

(1) Acquisition-station-dedicated data-transmission protocol. The acquisition station data-frame format was defined. Synchronous data-acquisition, digital transmission, and asynchronous data transmission functions were designed according to the actual needs of seismic-data acquisition, such that low-power and 16 Mbps high-speed data-transmission on a 55-m cable can be achieved.

(2) High-resolution ADC digital filtering technology. According to the features of Σ-Δ bit stream from the CS5373 modulator output, subsequent CIC, FIR and IIR hardware filters were designed.

(3) High-precision synchronous data acquisition. Asynchronous data-acquisition problems due to digital transmission delay of the data-acquisition stations were calibrated. The data-acquisition station synchronization accuracy was better than 200 ns.

(4) The high integration level of the hardware circuit. In addition to a small proportion of analog circuits and an ADC circuit, all of the digital integrated circuits and the core technologies of the digital seismic-data acquisition stations were integrated into a single-chip SoPC, to facilitate the subsequent tape-out.

The main advantages of our project are reflected in the above characteristics (2) to (4). The SoPC used in this study was a 65-nm CycloneIII series chip. If the digital circuits were rapidly transplanted into the current 28-nm SoPC, the power consumption would be further reduced. Meanwhile, to produce a highly integrated single chip for the analog-to-digital circuit, a future research area should be an in-depth study of high-precision Σ-Δ modulators, and on how to integrate these with the current core technology for the tape-out. Thus, while single-chip integration has been achieved, the performance of the data-acquisition station can still be further enhanced while significantly reducing power consumption.

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*Corresponding author: Deng Ming,
China University of Geosciences, Beijing, China;
email: dengming@cugb.edu.cn.