Design of a LabVIEW-Based Dual-Channel Solar Radio Spectral Observation System (Postprint)

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Abstract

Solar radio bursts represent an important manifestation of eruptive processes such as solar flares and coronal mass ejections, and constitute one of the potential influencing factors on satellite communications and navigation systems, ground power grid systems, and the human living environment. Monitoring and research of solar radio bursts can not only forecast space weather but also serve as a research tool for solar physics. This paper introduces a dual-channel high-speed solar radio spectrum observation system designed and developed based on the LabVIEW platform, which achieves monitoring of solar radio bursts given their characteristics of randomness, short duration, and rapid variation. The system employs a high-speed signal acquisition card for signal acquisition at a rate of 1.5 GS/s, achieving a temporal resolution of up to 4 ms and a frequency resolution of 45.7764 kHz. The acquired signals undergo power spectrum analysis via Fast Fourier Transform (FFT) and are then output and displayed as spectrograms and waterfall plots, obtaining information such as frequency, intensity, and duration of solar radio bursts. Observation data are uploaded to the server using File Transfer Protocol (FTP), enabling optimization of storage resources and sharing of observation data. The system features high integration and can be applied to analyze the 70–700 MHz signals output from the 11 m solar radio telescope at the Chenjiang-Fuxian Lake observation base.

Full Text

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Abstract

Solar radio bursts are important manifestations of solar eruptive processes such as solar flares and coronal mass ejections, representing one of the potential influencing factors on satellite communications and navigation systems, ground power grid systems, and the human living environment. Monitoring and studying solar radio bursts not only enables space weather forecasting but also serves as a research tool for solar physics. This paper introduces a dual-channel high-speed solar radio spectrum observation system designed and developed based on the LabVIEW platform, which aims to monitor solar radio bursts characterized by their randomness, short duration, and rapid variability. The system employs a high-speed signal acquisition card with a sampling rate of 1.5 GS/s, achieving a system time resolution of up to 4 ms and a frequency resolution of 45.7764 kHz. The acquired signals undergo Fast Fourier Transform (FFT) power spectrum analysis and are displayed as spectrograms and waterfall plots, providing information on the frequency, intensity, and duration of solar radio bursts. Observation data is uploaded to a server using the File Transfer Protocol (FTP), optimizing storage resources and enabling data sharing. This integrated system processes signals output by the solar radio telescope at the Chengjiang Fuxian Lake Observatory Base in the 70-700 MHz frequency range with high precision and can be applied to analyze solar radio bursts.

Keywords: solar radio; high-speed acquisition; LabVIEW; FFT power spectrum; FTP file transfer

1. Introduction

Solar eruptive activities have profound impacts on the space environment around Earth and human activities [**?**]. Intense solar eruptions generate and release large quantities of high-energy electrons into the corona. When these high-energy electrons couple with magnetic fields and hot plasma, they produce extremely intense electromagnetic radiation known as solar radio bursts [**?**]. Solar radio bursts are transient microwave signals radiated across a broad frequency band, with durations ranging from microseconds to minutes and frequencies extending from decameter to millimeter waves. Propagating at the speed of light throughout the sunlit side of Earth, they are accompanied by high-energy particles and cosmic rays that can affect the human living environment and cause interference or damage to satellite communications, navigation systems, and ground power systems [?].

Solar radio dynamic spectra are used to observe temporal and frequency variations of solar radio signals, providing information on signal intensity changes over time across frequency ranges from decameter to millimeter waves [?]. By studying the morphological characteristics of solar radio burst spectra, we can forecast various space weather effects on Earth following solar events [?] and investigate the relationship between solar radio bursts and solar flares, as well as shortwave fadeouts. Based on their distinct morphological features in radio dynamic spectra, solar radio bursts can be classified into different types, which are closely related to energy release and particle acceleration processes in solar activity and often exhibit fine structures [?].

Solar radio spectrometers require high temporal and spectral resolution to capture fine spectral structures within short timeframes. The primary function of solar radio dynamic spectrum analyzers is to measure frequency variations over time. Traditional swept-frequency spectrum analyzers are not only expensive but also unsuitable for real-time monitoring. However, rapid developments in Analog-to-Digital Converters (ADC) and Digital Signal Processing (DSP) technologies have laid the foundation for low-cost spectrum analysis instruments capable of real-time spectral analysis and signal parameter estimation [?]. Modern systems are evolving toward higher performance and modularization in both technology and design.

2. System Design and Architecture

This paper presents a dual-channel solar radio spectrometer developed using a high-speed acquisition system, comprising hardware acquisition and software analysis components. The system performs real-time analysis and processing of solar radio signals, monitors solar radio bursts, and enables optimized data storage and sharing. This capability enhances China's ability to monitor and forecast solar radio bursts, promotes theoretical research in solar physics, and provides open data access for researchers.

The overall structure of the solar radio telescope system is shown in [Figure 1: see original paper]. The system consists primarily of an antenna system, receiver, and high-speed digitizer. The antenna system receives solar radio signals and transmits them to the receiver. The receiver amplifies, frequency-converts, and filters the signals. Our developed dual-channel high-speed acquisition spectrum analysis system serves as the core of the entire solar radio telescope. The high-speed signal acquisition card and FPGA module function as the digitizer, converting analog signals to digital format and transmitting them via high-speed bus to the host computer. The host computer, based on the LabVIEW development platform, further processes the data to implement dual-channel solar radio spectrum observation, solar radio burst monitoring, and data storage and sharing via FTP.

3. Hardware Architecture

The system hardware primarily consists of the NI PXIe-1073 chassis, NI PXIe-7975R FPGA module, and NI-5771 FlexRIO digitizer adapter module, integrated to complete signal acquisition, spectrum analysis and display, and data storage and upload. The hardware connection method is illustrated in [Figure 2: see original paper]. The signal source connects to the modules inserted into the chassis slots, and the modules communicate with the host computer through the PXI Express data transfer interface.

3.1 FPGA Module The NI PXIe-7975R FPGA module features a Xilinx Kintex-7 FPGA core with 2 GB DDR3 DRAM for data buffering. The module operates with a fixed clock of 187.5 MHz. The high-speed performance of the PXIe-7975R and PXI Express bandwidth meets the transmission speed requirements for spectral data. Simulation experiments on the resources required for FFT processing algorithms confirm that the module's computational resources satisfy target requirements.

3.2 Digitizer Adapter Module The NI-5771 FlexRIO digitizer adapter module, combined with the FPGA module, forms a high-speed digitizer. It can simultaneously sample two channels at 900 MHz analog bandwidth with a rate of 1.5 GS/s per channel, or sample a single channel at 3 GS/s, with a sampling width of 8 bits. This configuration meets the requirements for high-speed sampling, high data flow rates, and high-performance deployment in the solar radio spectrum system.

3.3 Chassis and System Bandwidth The NI PXIe-1073 five-slot chassis provides two hybrid slots, offering a stable and reliable hardware platform with PXI Express bandwidth up to 250 MB/s, ensuring real-time data transmission.

3.4 System Technical Specifications According to Nyquist's first sampling theorem, an ADC sampling rate can completely recover low-pass signals with bandwidth up to half the sampling rate. The 1.5 Gsps sampling rate perfectly covers the 70-700 MHz band range of the solar radio telescope, making it an ideal replacement for the original swept-frequency spectrum analysis system operating at 200 Msps. With the sampling point number set to 32768 and sampling frequency at 1.5 Gsps, the frequency resolution Δf is calculated as:

$$\Delta f = \frac{f_s}{N} = \frac{1.5\ \text{Gsps}}{32768} = 45.7764\ \text{kHz}$$

where f_s is the sampling frequency and N is the number of sampling points. Table 1 presents the main technical indicators of the dual-channel solar radio spectrum observation system.

Main technical indicators of the dual-channel solar radio spectrum observation system

Index	Sample Rate (Gsps)	Frequency Range (MHz)	Spectral Resolution (kHz)	Temporal Resolution	Number of Sampling Points
1	1.5	70-700	45.7764	4 ms	32768

4. Dual-Channel Spectrometer System Design

The low-frequency solar radio spectrometer originally had a frequency resolution of 200 kHz. To analyze finer structures within solar bursts, we propose improving the frequency resolution to 50 kHz while maintaining appropriate temporal resolution. However, increasing frequency resolution leads to approximately double the data volume, which would cause unsustainable computational overhead. The dual-channel solar radio spectrometer first employs the NI-5771 module for data acquisition at 1.5 Gsps. The collected data is then processed through FFT operations on the FPGA. Given the observation range of 70-700 MHz and the symmetry of FFT results, the system discards data from 0-70 MHz and 700-1500 MHz ranges. This approach solves the problem of excessive data transmission time, processes two channels of data simultaneously, and avoids computational resource waste without losing original data.

5. Signal Processing Flow

The dual-channel solar radio spectrum observation system completes signal acquisition through a high-speed digitizer composed of NI-5771 and NI PXIe-7975R modules, achieving analog-to-digital conversion. The signal processing flow is shown in [Figure 3: see original paper].

5.1 FFT Algorithm and Frequency Domain Analysis The system first buffers ADC-sampled data in a First-In-First-Out (FIFO) memory, then performs FFT on the digital signal. After obtaining the power spectrum, it calculates the average power spectral density according to a preset integration time, stores the calibrated power spectrum data, and finally uploads local data to the server via FTP technology.

The signal processing flow primarily includes FFT computation. Utilizing Real-Time Spectrum Analysis (RTSA) technology ensures processing speed exceeds signal acquisition speed, guaranteeing seamless capture of signals into memory. The system leverages the FPGA module's parallel processing advantages for FFT calculations, achieving high-speed and stable data processing through data buffering.

Digital signal processing systems analyze signals in the frequency domain primarily through FFT. FFT is a fast algorithm for Discrete Fourier Transform

(DFT). When the sampling frequency satisfies the sampling theorem (greater than twice the signal's upper frequency limit), the digitized solar radio signals can be completely recovered. Due to the symmetry of FFT results, the output sampling points need to be converted to single-sided FFT by discarding half the frequency points.

According to the FFT butterfly algorithm, for a complex sequence of length N, its DFT can be calculated through FFT [?], [?], [?]. The implementation process recursively decomposes DFT into smaller DFTs, utilizing symmetry properties and twiddle factor characteristics for efficient computation. At each recursion level, the input sequence is divided into even-indexed and odd-indexed subsequences, then merged in the frequency domain. This process repeats until the complete frequency domain sequence is obtained.

Frequency domain analysis aims to identify spectral components in the acquired signals, including each constituent component and temporal variations in energy and amplitude for each frequency component. [Figure 4: see original paper] illustrates the FFT algorithm implementation flow.

6. Data Storage and Upload

The file data format is binary with big-endian byte order (network order). The dual-channel spectrum observation system operates daily from 00:00 to 10:00 UTC, with each file storing 1000 × 13761 data points. With a temporal resolution set to 47.1859 ms, the daily data file size reaches 78.2 GB. Local storage imposes high capacity requirements and makes remote data access difficult. Therefore, this design employs FTP to upload files to a server, achieving data sharing and alleviating local storage pressure. During implementation, the client and server communicate via FTP, with the client sending commands and receiving server responses to execute various operations.

7. Performance Testing

We conducted comprehensive testing of the dual-channel solar radio spectrum observation system, focusing on frequency resolution, dynamic range, and data auto-storage functionality.

7.1 Frequency Resolution Test Frequency resolution measures a digital signal processing system's ability to distinguish between two closely spaced frequency components. Table 2 records the actual power of the right-hand channel, demonstrating the system's ability to resolve frequency components separated by 45.7764 kHz. When the input frequencies differ by exactly one channel spacing (45.7764 kHz), the power difference exceeds 3 dB, confirming the system can distinguish adjacent frequency components at this resolution.

Actual power of collected signal in right-hand channel

Serial Number	Input Frequency (MHz)	Input Power (dBm)	Theoretical Channel	Actual Power (dBm)
1	74.981	-71.3	689	-71.3
2	149.965	-50.6	1379	-50.6
3	379.649	-54.2	3379	-54.0
4	978.638	-35.4	6368	-35.4
5	-	-20.5	-	-30.2
6	-	-	-	-73.2
7	-	-	-	-50.2

7.2 Dynamic Range Test Dynamic range characterizes the system's ability to simultaneously measure two signals with different amplitudes, defined as the ratio between the largest and smallest measurable signals. Using a signal generator, we recorded minimum power at -30 dBm and maximum power at 1 dBm. The measurement power fluctuation was less than 1 dBm at each frequency, with no significant deviation from transmitted power. Table 3 shows the dynamic range measurements for the left-hand channel across different input frequencies.

Dynamic range of left-hand channel

Serial Number	Input Frequency (MHz)	Minimum Power (dBm)	Maximum Power (dBm)
1	-	-40.4	-43.5
2	-	-43.3	53
3	754	-	-

7.3 Data Auto-Storage Function Test After launching the system and setting start/stop times and temporal resolution, we verified the auto-storage function upon observation completion. With a recording duration of 10 minutes and temporal resolution set to 4 ms, the system generated files totaling 7.69 GB. The program stores data in binary format, with each sample point occupying 8 bytes. Each 10-minute interval is stored as a fixed-size file of 53754 KB. The calculated temporal resolution matches the theoretical value of 4 ms, confirming no frame loss and validating the auto-storage functionality.

Right-hand channel data record generation details

Start Time	Stop Time	First File Creation Time	Last File Modification Time	Number of Files	Data Size
06:02:00	06:12:00	2022-10-20, 06:02:00	2022-10-20, 06:12:01	-	7.69 GB

8. Observation Results and Display

Balancing storage space, temporal resolution, and spectral resolution, the system was configured with a temporal resolution of 47.1859 ms for observations from 00:00 to 10:00 UTC. The signals observed by the dual-channel system originate from the 11-meter solar radio telescope at Chengjiang Fuxian Lake Observatory Base in the 70-700 MHz range. The software interface displays real-time spectrograms and waterfall plots, as shown in [Figure 6: see original paper].

Since commissioning, the system has observed multiple solar radio bursts of varying intensities on February 20, 2023 (02:20-02:40 UTC) and March 16, 2023 (01:46-01:51 and 03:16-03:19 UTC), including Type III bursts and fine structures. The observed spectrogram waterfall plots are presented in [Figure 7: see original paper] and [Figure 8: see original paper].

9. Conclusion

The designed dual-channel solar radio spectrum observation system based on LabVIEW achieves high-speed acquisition of broadband signals, real-time digital signal processing, spectrum analysis and display, solar radio burst monitoring, and automatic data storage and upload functions. The interface design is concise, operation is efficient, and measurement accuracy is high. After more than half a year of trial operation, the system has captured numerous solar radio bursts and their fine spectral structures, demonstrating its capability for long-term observations. It will play an important observational role in solar physics and space weather research during the upcoming solar activity cycle maximum.

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Note: Figure translations are in progress. See original paper for figures.