Postprint of the Development of an Ultra-Wideband Ultra-High Resolution Solar Radio Spectrometer

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Abstract

To monitor the 15 MHz–15 GHz spectrum of solar radio bursts, the Yunnan Astronomical Observatory has developed four solar radio spectrometers with frequency coverage ranges of 15–80 MHz, 100–750 MHz, 600–4200 MHz, and 4–15 GHz, respectively designated as the decameter-wave, meter-wave, decimeter-wave, and centimeter-wave solar radio spectrometers. The decameter-wave solar radio spectrometer achieves a spectral resolution of 7.6 kHz and a time resolution of 1 ms; the meter-wave and decimeter-wave solar radio spectrometers achieve spectral and time resolutions of 9.5 kHz and 10 ms, respectively; the centimeter-wave solar radio spectrometer achieves spectral and time resolutions of 76 kHz and 10 ms, respectively. Each system comprises an antenna assembly, receiver, and digital spectrometer. To attain ultra-high spectral resolution, the required Fast Fourier Transform (FFT) point count reaches 262,144, which cannot be realized through a single FFT Intellectual Property (IP) core on a Field Programmable Gate Array (FPGA). For large-point FFTs, parallel processing following row-column decomposition of the data is necessary, thereby converting it into two smaller-point FFTs. Through investigation of parallel algorithms, Matlab was employed to simulate the algorithm, which was subsequently implemented in the digital spectrometer. The digital spectrometer test results exhibit excellent consistency with the simulation results, confirming the successful implementation of the algorithm. This work primarily presents the architecture of the solar radio spectrometer and the methodology for achieving ultra-high spectral resolution based on FPGA.

Full Text

Preamble

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Development of Ultra-Wideband Ultra-High Resolution Solar Radio Spectrometer

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Abstract

To monitor solar radio bursts across the 15 MHz–15 GHz spectrum, Yunnan Observatories has designed and developed four solar radio spectrometers covering 4–15 GHz, 600–4200 MHz, 100–750 MHz, and 15–80 MHz, designated as the decametric, metric, decimetric, and centimetric solar radio spectrometers, respectively. The decametric spectrometer achieves a spectral resolution of 7.6 kHz and temporal resolution of 1 ms; the metric and decimetric spectrometers achieve 9.5 kHz and 10 ms, respectively; and the centimetric spectrometer achieves 76 kHz and 10 ms. Each system comprises an antenna system, receiver, and digital spectrometer. To achieve ultra-high spectral resolution, FFT lengths up to 262,144 points are required, which cannot be realized through a single IP core implementation on FPGA. For large-point FFTs, data must be decomposed into rows and columns for parallel processing, transforming the computation into two smaller-point FFTs. This paper investigates the parallel algorithm, simulates it using MATLAB, and implements it in the digital spectrometer. Test results demonstrate good consistency with simulations, confirming successful algorithm deployment. The paper primarily introduces the spectrometer composition and the FPGA-based method for achieving ultra-high resolution.

Keywords: spectrometer; ultra-wideband; ultra-high resolution; FFT

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1. Introduction

Solar activities such as coronal mass ejections (CMEs) represent the most violent energy releases in the solar system. The radio emissions produced during these processes carry information about coronal plasma and magnetic fields [1], while high-energy particles and cosmic rays generated can disturb the space environment and Earth's magnetic field, directly affecting satellites, power grids, and other modern technological systems that influence human life [2–4]. With China's rapid aerospace development, space weather has become a research focus in solar physics. Solar radio dynamic spectra are crucial for observing solar radio bursts, and improved spectral and temporal resolution has enabled the discovery of various fine structures (Types I, II, III, IV, etc.) [6–9]. High-resolution dynamic spectra are vital for understanding the physical mechanisms of solar radio bursts [10], providing information about coronal magnetic fields and plasma—plasma radiation reveals plasma density, while gyro-synchrotron radiation provides magnetic field information [11]. Dynamic spectra also enable space weather forecasting; for instance, Type II burst drift rates can estimate shock velocities, making them important for space weather warnings [12–13].

The solar radio spectrometer under the Meridian Project II Interplanetary Monitoring Chain subsystem, located in eastern China, will cover 30 MHz–15 GHz (https://www.sjdz.org.cn/cn/article/doi/10.19975/j.dqyx.2023-016). The spectrometers described herein are deployed in western China, enabling coordinated observations that extend continuous monitoring periods and enhance real-time space weather forecasting capabilities.

2. System Composition

The ultra-wideband ultra-high resolution solar radio spectrometer consists of four independent systems. The digital spectrometer, developed as an FPGA-based digital backend, represents the critical component. Based on ultra-high resolution requirements and leveraging digital signal processing flexibility, the maximum FFT length reaches 262,144 points. Since a single FPGA IP core cannot implement such large-point FFTs, the Cooley-Tukey FFT algorithm decomposes the data into channels for parallel processing, completing the required FFT through data recombination [14].

2.1 Overall Architecture

The spectrometer composition is shown in [Figure 1: see original paper]. The system comprises three main parts: antenna system, receiver, and digital spectrometer. The antenna receives solar radio emissions and transmits them to the receiver, which amplifies, frequency-converts, and filters the signals. The digital spectrometer performs sampling and spectral analysis, then transmits spectral data to a computer for storage.

Antenna System: From centimetric to decametric bands, the antenna systems include a 12 m parabolic reflector with quadridge horn feed (centimetric), 6 m parabolic reflector with quadridge horn feed (decimetric), 6 m parabolic reflector with log-periodic feed (metric), and log-periodic antennas (decametric). All employ equatorial mounts capable of automatically calculating solar orbital parameters for precise tracking.

For a 6 m parabolic antenna, the half-power beamwidth (HPBW) is given by HPBW $= 1.22\lambda/\mathrm{D}$, where λ is wavelength and D is antenna diameter. At frequencies above 7 GHz, beamwidth falls below 0.5°, insufficient to cover the entire solar disk. Beam-shaping technology expands the beamwidth beyond 0.5°. Simulation results in [Figure 0: see original paper] show HPBW values of 0.78°, 0.58°, 0.54°, and 0.50° at 6 GHz, 9 GHz, 12 GHz, and 15 GHz, respectively, meeting the requirement for full solar disk coverage.

Receiver Design: Four receivers cover centimetric, decimetric, metric, and decametric bands. Each performs low-noise amplification, gain control, and frequency conversion. The decimetric and centimetric receivers have wide bandwidths, requiring filter banks to segment the frequency range into multiple IF channels. IF channel bandwidth is designed as 1 GHz (0.1–1.1 GHz output) to balance receiver complexity and digital spectrometer requirements. The centimetric and decimetric receivers switch between left- and right-circular polarization, while the metric and decametric receivers, having narrower bandwidths, simultaneously sample both polarizations through two channels, reducing hardware costs without significantly decreasing integration time.

Each receiver includes a calibration system with microwave switches, low-noise amplifiers (LNAs), polarization synthesizers, and analog receivers. The LNA provides low-noise amplification; polarization synthesizers convert linear to circular polarization; analog receivers handle amplification, optical transmission, and frequency conversion. Digital attenuators in the mixing components provide 30 dB gain adjustment, increasing dynamic range. Measured specifications for all receivers are listed in .

2.2 Digital Spectrometer Implementation

The digital spectrometer is a standard VPX-6U architecture data acquisition and processing platform consisting of carrier boards and daughtercards. The high-speed backplane enables inter-board communication, while the FMC-HPC interface allows daughtercard interchangeability. The physical structure is shown in [Figure 5: see original paper].

The carrier board is an FPGA-based digital signal processing board equipped with two JFM7Vx690T36 FPGAs, each processing one channel. DDR3 SDRAM modules provide data buffering. The FPGA's streaming and parallel architecture facilitates algorithm implementation. The ADC daughtercard uses the ADI AD9625 (2.5 Gsps, 12-bit, 71 dBfs SFDR, >8.5 effective bits), meeting dynamic range requirements. The communication daughtercard supports both 10/100M Ethernet and fiber optic communication at 10 Gbps, ensuring real-time spectral data transmission.

3. Parallel FFT Algorithm

The digital spectrometer's core algorithm is real-time FFT computation. While FPGAs can directly call FFT IP cores, their maximum transform length cannot meet project requirements. With ADC sampling at 2.5 Gsps and FPGA clock speeds limited to 312.5 MHz, parallel FFT algorithms are necessary. The design employs 8 parallel channels, each performing 32,768-point FFTs at 312.5 MHz.

3.1 Algorithm Principle

For an N-point sequence x, the Cooley-Tukey FFT decomposes the transform by arranging data into an M×L matrix (N = M×L). The algorithm consists of: 1. Row FFTs on the matrix 2. Multiplication by twiddle factors W_{mk} 3. Column FFTs 4. Data recombination

This converts a one-dimensional N-point FFT into two-dimensional M×L-point FFTs with parallel processing. The signal flow is illustrated in [Figure 6: see original paper].

3.2 Simulation and Verification

The parallel FFT algorithm was simulated in MATLAB using a 762.94 MHz sinusoidal input with 2.5 Gsps sampling and 32,768-point FFT length. [FIGURE:7(a)] shows the MATLAB simulation, while [FIGURE:7(b)] displays FPGA implementation results. The nearly identical outputs confirm successful algorithm deployment. The same verification was performed for 262,144-point FFTs with consistent results.

4. Conclusion

The four spectrometers collectively cover 15 MHz–15 GHz, monitoring solar radio bursts from the coronal base to two solar radii—the region where initial energy release, shock formation, and particle acceleration occur. The system achieves ultra-high spectral and temporal resolution comparable to or exceeding international instruments, providing valuable data for both solar radio research and space weather forecasting. While antennas are under construction, receivers and digital spectrometers are complete. Test data confirm that parallel FFT enables large-point transforms and high-resolution spectra. Coordinated observations with domestic instruments such as the radio heliograph, decimetric radio spectrograph, and Daocheng Radio Heliograph will enable comprehensive solar radio studies.

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