

Postprint: High-Performance Chip-Based Radio Astronomy Centimeter-Decimeter Wave Spectral Line Observation Method

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Abstract

Spectral line observations play a crucial role in astronomy, as higher spectral resolution facilitates the study of celestial details. However, achieving high spectral resolution using traditional sampling methods is extremely challenging in high-frequency spectral line observations. Currently, a novel method implemented with high-performance chips for radio astronomy centimeter-decimeter wave spectral line observations has overcome many limitations of conventional approaches, enabling high spectral resolution with relatively low sampling bandwidth. This constitutes a complete solution for data acquisition, processing, and storage. The process involves analog down-conversion of high-frequency signals, followed by Fast Fourier Transform and integration processing of the resulting low-frequency signals via host computer software, with final storage in the required file format. All system acquisition parameters are configured by observers through the host computer software.

Full Text

A New Method for Radio Astronomy Centimeter-Decimeter Spectral Line Observation Based on High-Performance Integrated Circuits

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Abstract

Spectral line observation plays a crucial role in astronomy, as high spectral resolution greatly facilitates the study of celestial details. However, achieving high spectral resolution in high-frequency bands using traditional sampling methods presents significant challenges. This paper proposes a novel approach for radio astronomy centimeter-decimeter spectral line observation that leverages high-performance integrated circuits to overcome many limitations of conventional methods, enabling high frequency resolution with relatively low sampling bandwidth. The system provides a complete solution for signal acquisition, processing, and storage. High-frequency signals first undergo analog down-conversion, after which the resulting low-frequency signals are processed by host computer software for Fast Fourier Transform (FFT) and integration, before being saved in the required file format. All acquisition parameters are configured by observers through the host software interface.

Keywords: FPGA; Agile transceiver; Radio astronomy; Spectral line observation; Frequency resolution

1. Introduction

Spectral line observation is essential for obtaining information about celestial objects. High-frequency observations require data acquisition equipment with increasingly higher sampling rates, and major chip manufacturers have been developing faster, higher-bandwidth data acquisition chips, some of which have already been applied in radio astronomy. However, the drawbacks of high-speed data acquisition include wasted resources on frequency bands lacking observable signals. With the rapid advancement of integrated circuit technology, a new observation and control method has emerged [1-2].

Spectral lines hold a pivotal position in radio astronomy observations, providing diagnostics of basic physical and chemical properties of celestial bodies. By observing molecular lines, researchers can study velocity fields in molecular motion regions, magnetic field strengths, chemical abundances of various elements, and other parameters. After obtaining spectral line data from molecular clouds and star-forming regions, the statistical equilibrium radiative transfer equation can be solved using appropriate approximation methods to derive various information about the target object. Molecular spectral line observations enable investigation of numerous astronomical phenomena, including early-stage star-

forming regions, late-stage stellar evolution, supernova explosions, planetary nebulae, and extragalactic systems [3-5].

Recent research hotspots include: (1) Studies of methanol masers at 6.7 GHz, which have become a major focus in astronomy and astrometry due to their compact size (a few astronomical units), extremely small internal proper motions, and radiation flux characteristics. These are used not only for research on massive star formation but also for precise determination of key Galactic parameters such as spiral arm structure through parallax measurements—currently the highest-precision method available for such studies. (2) Research on hydroxyl and formaldehyde spectral lines, including formaldehyde sample surveys and their radiation characteristics, as well as OH maser searches and magnetic field studies through OH polarization observations. (3) Numerous other research topics including molecular line searches in various bands.

2. Challenges with Traditional Methods

High spectral resolution observations can reveal more detailed information about target objects, typically tracing smaller-scale structures and more detailed kinematic features. Certain high-precision observations require extremely high frequency resolution. For example, in Zeeman effect observations using the neutral hydrogen line at 1.667 GHz, a microgauss magnetic field produces only a 2.8 Hz frequency shift; at 1.665 GHz, the shift is 3.27 Hz; and at 1.96 Hz for the 1.667 GHz line. Traditional radio astronomy backend systems rely on high-speed analog-to-digital converters (ADCs) for radio signals. According to sampling theory, an ADC with sampling rate f_{sample} can cover approximately $f_{\text{sample}}/2$ bandwidth. Currently, increasing sampling rates has become the only solution for large-bandwidth data acquisition and wideband simultaneous observations [3-5].

For a given velocity dispersion, the corresponding spectral width can be determined through the Doppler relationship. Based on the relationship between sampling rate f_{sample} , FFT points N , and spectral resolution Δf [4], the velocity resolution depends on sampling rate, center frequency, and FFT points N —higher sampling rates result in lower velocity resolution [4-5]. Under traditional sampling principles, high-precision profile observations of spectral lines are extremely difficult because achieving higher spectral resolution requires increasing FFT points N at a fixed sampling rate, which consumes substantial FPGA multiplier, accumulator, and memory resources while generating large amounts of redundant data that must be analyzed even for frequency bands without signals.

Major chip and modular instrument companies have subsequently developed even faster, higher-bandwidth data acquisition chips and equipment. Examples include the Acqiris AC240 (1 GHz @ 8-bit) used at the Delingha 13.7 m millimeter-wave telescope and the KOSMA 3 m millimeter-wave telescope, as well as the backend developed by B. Klein et al. [3,5], all representing the

fastest radio astronomy backends currently available. However, according to atomic stimulated emission characteristics, radio astronomical spectral lines exhibit discrete, locally dense line spectra with very few observable lines. The advantages of high-speed data acquisition are wasted on frequency bands without observable signals.

For example, observing a maser source with 100 MHz bandwidth but only 8 MHz of actual observation bandwidth requires 488.3 Hz resolution. This necessitates 488.3 kHz FFT points in full-bandwidth mode, equivalent to 488.3 kHz points in narrowband mode—a relationship summarized in the bandwidth vs. FFT points diagram [Figure 1: see original paper]. As acquisition speeds increase, the required FFT points for a given frequency resolution increase proportionally.

3. Digital Down-Conversion Approach

To address these issues, researchers attempted to establish a digital backend based on undersampling at the Effelsberg 100 m radio telescope in 2005 [6], introducing the concept of direct digital down-conversion (DDC). The digital spectrum analysis terminal ICS-554C (Digital Down Converter) from IC-Converters operates in two modes: (1) Full-bandwidth mode, where signals are directly sampled by the ADC into the FPGA for FFT analysis; (2) Narrowband mode, where signals are selected by the DDC before being sent to the FPGA for processing. The observation effects of these two modes on the same spectral line are shown in [Figure 2: see original paper].

The narrowband mode observations of neutral hydrogen and OH masers in 2 MHz bandwidth demonstrate that higher resolution can be achieved [FIGURE:3, FIGURE:4]. However, both approaches increase circuit complexity. With today's integrated circuit technology, new integrated circuits can replace these solutions. Analog Devices' AD936x series represents a new generation of high-performance, highly integrated RF Agile Transceiver ICs.

4. AD9361 Agile Transceiver Solution

The AD9361 agile transceiver is an ideal choice for various transceiver applications due to its programmability and wide bandwidth. This device integrates RF front-ends with flexible mixed-signal baseband, covering most licensed and license-exempt frequency bands with channel bandwidths from less than 200 kHz to 56 MHz. Compared to traditional high-speed sampling digital spectrum terminals, this solution achieves 6 GHz input bandwidth at only 200 kHz sampling rate, equivalent to a 12 Gsps sampling rate—improving frequency resolution by the same FFT points by a factor of 60,000.

The system employs advanced integrated RF agile transceivers to develop a new dedicated spectral line receiver, enabling fast, switchable wideband radio astronomy backends and associated software. This provides high-precision spectral line observations for the Yunnan Observatories radio telescope.

The AD9361 is a typical representative of agile transceiver solutions, supporting 70 MHz to 6.0 GHz frequency range and 200 kHz to 56 MHz channel bandwidth [Figure 200: see original paper]. Two independent direct-conversion receivers feature industry-leading noise figure and linearity. Each receiver subsystem includes independent Automatic Gain Control (AGC), DC offset correction, quadrature correction, and digital filtering, eliminating the need for these functions in digital baseband. The device also offers flexible manual gain modes.

Each channel incorporates two high-dynamic-range ADCs that digitize received signals before passing them to configurable decimation filters and Finite Impulse Response (FIR) filters, generating results at the corresponding sampling rate. The AD9361 primarily selects the required observation band based on commands from the control system.

5. Hardware Platform Implementation

The hardware platform utilizes the Xilinx Zynq-7000 SoC ZC702, Xilinx' s latest platform solution in 28 nm process technology. In addition to traditional high-performance FPGA fabric, the Zynq SoC integrates two ARM Cortex-A9 processor cores capable of running Linux. This enables convenient control of FFT operations within the FPGA and communication with data storage devices such as Linux workstations, while leveraging Linux' s comprehensive networking capabilities for system integration.

During operation, the FMC-LPC interface sends control signals to the AD9361 agile transceiver board to select the desired observation band. The AD9361 transmits sampled data to the FPGA portion of the XC7Z020 for baseband signal reception, followed by FFT and calibration operations. The entire data processing sequence executes under Linux program monitoring, which also provides human-machine interfaces for effective parameter setting and modification.

After FPGA processing, the signal data bandwidth is significantly reduced to levels that can be handled by the ARM A9 processor for real-time storage and transmission. The Linux system provides complete file system and network functionality for real-time storage and transmission of processed data.

6. System Implementation and Results

The AD9361 agile transceiver system based on the Xilinx ZC702 FPGA development board was implemented as follows:

1. **System Preparation:** Download the system image file from Xilinx' s official website, decompress it, and use Win32DiskImager software to write the 2014_R2-2015_02_06.img.xz image to an SD card. Important: Ensure the SD card drive is selected as the target device and verify the correct image file path before clicking "Write." After writing, safely eject the card. Note: The SD card contains boot images for various development boards; copy the image file from the "zynq-zc702-adv7511-ad9361-fmcomms2-3"

subdirectory to the SD card root directory to create the bootable image for the FMCOMMS2-EBZ board.

2. **Hardware Setup:** Connect the AD-FMCOMMS2-EBZ board to the ZC702 FPGA development board via the FMC connector, then connect the radio telescope's IF receiver output to the AD9361 receiver input (6 GHz bandwidth for direct sampling below 6 GHz).
3. **Network Configuration:** On the control computer (Windows 7 64-bit PC), open Settings → Network Connections → IPv4 Settings and set the IP address to 169.254.188.133. This establishes communication between the FPGA development board and host computer.
4. **Software Installation:** Install the agile transceiver application (IIO Oscilloscope) on the host computer, launch the application, and establish connection by entering the IP address (169.254.188.133) and port to access the parameter configuration interface.
5. **Operation:** Select the FMCOMMS2/3/4 tab and run. The system clearly displays peaks near 751.4 MHz [Figure 6: see original paper]. Compared with commercial spectrum analyzer results [Figure 7: see original paper], the agile transceiver spectral line observation terminal demonstrates excellent performance.

7. Conclusion

The agile transceiver system combining FPGA with AD9361 successfully implements narrowband spectral line observation for radio astronomy centimeter-decimeter bands. The integrated chip approach can effectively replace traditional discrete analog down-converters, analog filters, high-speed ADCs, and high-performance FPGA-based observation systems while ensuring reliability for astronomical observations. This system will play an increasingly important role in future astronomical observations.

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

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