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Construction and Application of a Teaching Experimental System for Solar Radio Telescopes

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Abstract. This article introduces the construction ideas and methods of a teaching and experimental system for solar radio telescopes. The system has the functions of automatic collection of observation data, automatic analysis and processing, automatic generation and transmission of products, as well as system calibration and self inspection. In response to the needs of course teaching, five experiments were conducted, including observation of electromagnetic radiation intensity in space background, observation of peaceful solar radiation, observation of lunar radio and etc., effectively improving the practical teaching effect of the course.

Keywords: solar radio telescope, teaching experiments, upper computer software

1 Introduction

The sun is the source of the space environment, and solar activity causes disturbances and changes in the near earth space environment. The monitoring of the space environment needs to be carried out at multiple levels, including the sun, interstellar space, magnetosphere, ionosphere and mid to upper atmosphere. These monitoring contents include: solar surface and solar activity, interplanetary solar wind, magnetospheric particles, electromagnetic environment, ionosphere, mid to high altitude atmospheric plasma, neutral components, etc. In addition, on the basis of spatial data observation, it is necessary to store, process and analyze continuous observation data to meet teaching and research needs [1,2].

The RF front-end of the existing centimeter band solar radio telescope is very complex[3], making it difficult to expand new functions, or filtering and frequency conversion make the system large and complex, significant fluctuations in the band and severe signal distortion, it results in low time and frequency resolution of the collected centimeter band solar radio telescope. In response to these issues, this article constructs a high-frequency and broadband solar radio signal observation system, which can meet the requirements of continuous observation of 2-10 GHz radio signals by high-frequency radio telescopes, and can monitor the spectrum and partial flow of

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solar radio signals in the 2-10 GHz frequency band in real time. It has wide observation frequency band, good real-time performance and calibration function. This system has high time resolution and frequency resolution, that is, a maximum time resolution of 2.4 ms and a maximum frequency resolution of 0.15 MHz. It can achieve high-frequency and broadband signal data acquisition and processing of astronomical radio signals. Based on the practical teaching of space environment courses, a radio telescope teaching experimental system capable of observing the sun has been constructed, effectively improving the level of practical teaching.

2 Overall Design Strategy of the System

The solar radio telescope system is a highly automated space exploration equipment, which has the functions of automatic collection of observation data, automatic analysis and processing, automatic generation and transmission of products, as well as system calibration and self inspection. At the same time, it has high reliability and stability, and can operate continuously for a long time.

The solar radio signal observation device includes a five meter parabolic antenna, an analog front-end system, a digital receiver, and a storage system. It also includes a set of workstations and data processing software. It can achieve real-time monitoring of the spectrum and partial flow of solar radio signals in the 2-10 GHz frequency band, and has a wide observation frequency band, good real-time performance, and calibration function.

The preferred receiving antenna is a large aperture five meter parabolic antenna with a left and right circularly polarized antenna feed, and outputs left and right circularly polarized signals. The five meter antenna system is used to support radio observation of the sun and moon. It is capable of utilizing the trajectory of the sun to achieve program tracking, and has designated, standby, manual, bookmarking and other working modes.

The simulation front-end system adopts a combination of direct sampling and frequency conversion, which can amplify and filter the 2-10 GHz frequency band, and mix some frequency bands. The channel switching of the analog front-end system is controlled by the TTL level output by the digital receiver. When the digital receiver completes the analog signal acquisition of one channel, it changes the TTL control level to allow the analog front-end system to output the analog signal of the next channel. In this way, the signal acquisition of the used channel is completed and this operation is continuously cycled.

The digital receiver uses a dual channel 2.6 Gsps acquisition board to collect two signals. The collected and processed signals are transmitted through optical fibers to the display and storage system for display and storage. The digital receiver mainly consists of high-speed ADC and high-performance FPGA. When the digital receiver is working, the high-speed ADC first collects the intermediate frequency signal processed by the analog front-end unit, converts the analog signal into a digital signal, and then transmits the data to the FPGA for digital processing through the JESD204B high-speed interface. The processing content includes data windowing, FFT operation, data accumulation processing, etc. The processed data can be transmitted to the upper computer through fiber optic or PCIe interface for display and storage functions.

The main functions of the upper computer software include continuous data collection, real-time display of images and continuous storage of files. It mainly includes three parts. (1) The main program, which completes software initialization, parameter configuration, image display, and responds to user input instructions. (2)The data collection thread completes the work of data collection, caching, and transfer. (3) The data storage thread completes the data storage work. When the upper computer is running, it first starts the data acquisition function of the system, and then the digital receiver outputs the raw data to the upper computer. After obtaining data, the upper computer starts the storage function, starts storing data and plots and displays the full frequency spectrum curve and spectrum image for display from the real-time data obtained. At the same time, the upper computer sets up the corresponding frequency point power display function to plot and display a specific frequency point separately. After completing the above functions, users can decide at their own discretion when to stop collection and storage.

3 System Composition

The solar radio telescope system mainly consists of receiving antennas, signal analog processing, digital processing, measurement, control, analysis, display and storage. The antenna receiving unit can achieve automatic tracking and program tracking of the antenna towards the sun, thereby ensure that the antenna always automatically and accurately targets the sun and receives electromagnetic radiation signals from the sun within the specified daily observation time. Signal analog processing and digital processing functions are respectively achieved by analog receivers and digital receivers. The spectrum display and flow display of solar radio signals are achieved by the upper computer and corresponding operating software.

The solar radio telescope observation system consists of receiving antenna, servo control, antenna control computer, control software, analog receiver, digital receiver, calibration unit, data storage and display system modules. The system structure is shown in figure 1.

The various modules of the solar radio telescope are introduced as follows:

(1) receiving antenna

The receiving antenna mainly includes a parabolic reflector, a dual circularly polarized feed antenna and a tracking control turntable. The system equipment has fully automatic control function and real-time high-precision tracking of the sun. The main technical indicators include: operating frequency band 2-10GHz, antenna aperture of 5 meters, antenna gain ≥ 30dB, and polarization mode of left and right circular polarization.

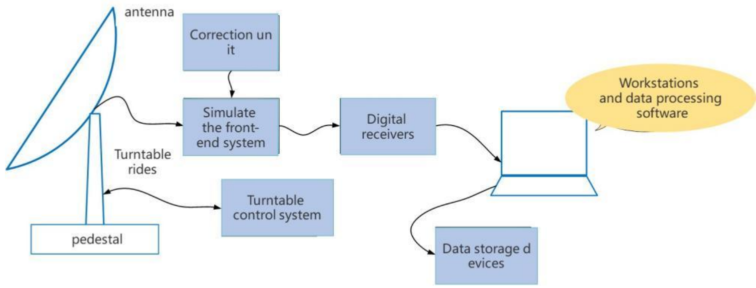

Fig. 1. Structural diagram of the solar radio telescope.

(2) Servo control, antenna control computer and control software

The main function of the system is to ensure that the antennas on the platform can accurately align with the sun and moon, and have a certain degree of pointing accuracy. When tracking the sun, it is necessary to make sure that the antennas can aim at the sun and receive electromagnetic radiation signals from the sun, and track the sun in real time. At the same time, it can also be remotely controlled by humans when needed [4].

The tracking methods that can be set by the antenna control computer are program control or manual control to ensure that the pointing accuracy of the receiving antenna is better than 1/10 beamwidth and the tracking accuracy is better than 1/10 beamwidth. Servo control and antenna control computers have communication functions with other computers, as well as local and remote control functions. The control software can display information such as time, antenna position, motion status, longitude, latitude, height, etc. It can also run directly on the workstation to achieve remote control of the antenna and servo system.

(3) Analog receiver

The analog receiver mainly amplifies, filters, downconverts, and channels the 2-10 GHz analog signal output by the antenna, and sends it to the digital receiver after processing. The analog receiver divides the receiver into multiple frequency bands to achieve full coverage of the 2-10 GHz frequency band. The frequency band division scheme is carried out, and appropriate adjustments need to be made according to the interference situation of the electromagnetic environment during actual observation. The main technical indicators include: channel instantaneous bandwidth 3GHz, noise coefficient $\leq$ 2.5 dB (typical value), gain $\geq$ 60 dB, and local oscillator output frequency phase noise, respectively, $\leq$ -130 dBc/Hz@100 Hz, $\leq$ -155 dBc/Hz@1 KHz, $\leq$ -165 dBc/Hz@10 KHz, mirror suppression $\geq$ 70 dB, mid band out of band suppression $\geq$ 70 dB, channel switching time $\leq$ 80ns, analog receiver controls channel switching, channel polling time, etc. by digital receiver instructions.

(4) Digital receiver

The digital receiver mainly includes a high-speed analog-to-digital converter (ADC) and an FPGA spectrum analysis and processing unit. The high-speed ADC first converts the solar radio signal processed by the analog front-end unit into a digital signal, performs FFT transformation on the solar radio digital signal, converts the time domain into frequency domain data, and performs average operation within the time resolution to reduce noise and improve signal-to-noise ratio. At the same time, it reduces the amount of data in the high-speed data stream, and uploads it to the workstation through PCIe or optical fiber for processing by computer software, and store the recorded solar radio dynamic spectrum data in the disk array. The main technical indicators include: 4 channels, configurable sampling rates of 3 GPSS, 2.6 GSPS, 1.3 GSPS, etc., resolution bits of 14 bit, dynamic range SFDR better than 55 dB, with synchronization function with Beidou and GPS signals, supporting various transmission speeds such as 1 Gsps, 10 Gsps and 40 Gsps.

(5) Upper computer display and storage

The upper computer display and storage section includes a data quality detection module, a data calibration, spectrum mapping module and a storage module. It is mainly used for storing solar flare spectrum data obtained from 2-10 GHz solar radio telescopes, data quality inspection, calibration with calibration units and spectrum data mapping functions. The spectrum data is ultimately transmitted to a disk array for storage [5]. The functions of data processing software include spectrum imaging display, radiation flow display, data calibration, storage control, and judgment and reporting of solar radio bursts. It also is equipped with turntable control function. Its data display refresh rate ≤ 1 s. The workstation processor has a main frequency of 3 GHz, memory of 16 GB, and a hard disk capacity of 2 TB. The data storage device has a storage capacity of 144 TB, a network port speed of 10 Gigabit, and a network port quantity of 4.

The data quality monitoring module performs data quality detection on the spectrum data transmitted by the corresponding digital receiver through Ethernet. Data calibration is the use of microwave switches to select noise sources and calibrate resistors to obtain calibration coefficients, which in turn obtain the calibrated energy unit dBm of the collected data, and convert it into standard solar radiation intensity in units of SFU. As shown in figure 2 (a), based on the calibrated data, the upper computer performs spectral imaging on the data. And the spectral imaging function specifically presents the relationship between time, frequency and solar radiation intensity [6]. The calibrated solar radiation intensity SFU quantifies the color changes, forming multiple colors and gradients with different colors representing spectral images of solar radiation intensity of different intensities. As shown in Figure 2 (b), a specific frequency point is selected based on the calibrated data for real-time display of solar radio flux.

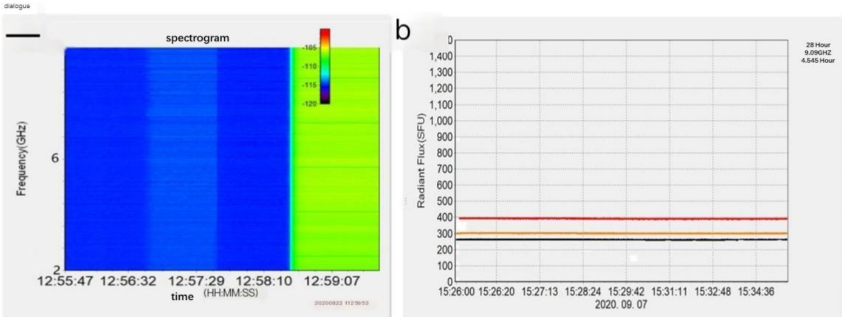

Fig. 2. Radio spectrum imaging and radiation flow observation effect diagram.

The upper computer display interface is shown in figure 3. The left side of the control interface has two windows: spectrum display and typical frequency point radio flow display, which can display the solar radio spectrum of 2-10 GHz and the radiation flow of solar radio at related frequency points. The right side has the relevant control button section, which completes functions such as storage, display and calibration.

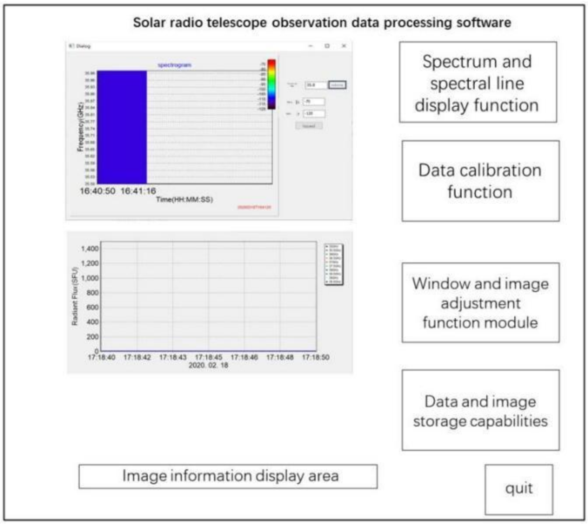

Fig. 3. Schematic diagram of the software interface for the upper computer of the solar radio telescope.

(6) Calibration unit

The calibration unit is used to calibrate the solar radio brightness temperature value received by the antenna. Due to the receiver's own gain and noise coefficient not being ideal and constant, it is necessary to calibrate the power value of the radio input within a certain time interval. There are two calibration sampling methods, one is regularly pointing to the positive sky, and another is calibrating by the calibrated noise source. The noise source indicators include: output frequency range of 0.1-18 GHz, super noise ratio ≥ 14.5 dB, standing wave ratio ≤ 1.2 dB (typical value) and noise output flatness ≤ 1 dB.

The relative calibration method for regularly pointing towards the sky is to use the upper computer to control the antenna tracking control system to periodically point towards the sky, and then compare it with the power value when facing the sun, in order to obtain the relative value of solar radio radiation intensity [7]. Using calibrated noise sources for calibration, this method requires calibrating the antenna and then calibrating the analog front-end and receiver as a whole. Regularly alternating between cold and hot sources by microwave switches, two power values are obtained through cold and hot sources, and a straight line is fitted to derive the output power of the antenna.

4 Teaching Experiments

The solar radio observation teaching experimental system is used to support solar radio observation experiments, consisting of a solar radio telescope and related teaching operation platforms. It can not only provide spectral observation capabilities of 2-10 GHz, but also provide radio radiation flow observations at three typical frequency points with wavelengths of 10.7 cm, 6.6 cm, and 3.3 cm. The data collected by the solar radio telescope is transmitted to the upper computer indoors for real-time storage and display of observation data.

Based on solar radio observation equipment and corresponding software, five experiments were conducted, including quiet solar radiation observation, space background electromagnetic radiation intensity, lunar radio observation, solar burst observation and antenna reception effect in space observation. The details are as follows:

(1) Observation experiment of electromagnetic radiation intensity in space background

By testing the intensity of electromagnetic radiation in the space background, it can evaluate the level of electromagnetic radiation in the space environment, ensure the normal operation of space devices, promote space scientific research, ensure the safety of astronauts and the stable operation of radio telescopes. The observation experiment of electromagnetic radiation intensity in space background is conducted by using a solar radio telescope to observe the electromagnetic radiation phenomenon in space background. The experiment helps students understand the impact of spatial electromagnetic environment on radio telescopes and enhances their cognitive ability towards electromagnetic radiation.

(2) Peaceful solar radiation observation experiment

There are electromagnetic waves of various wavelengths in the universe, and the Earth's atmosphere absorbs most of the electromagnetic waves from the universe. Only visible light and some radio waves can penetrate the atmosphere. Astronomers refer to this portion of radio waves as radio waves. The human eye does not have the natural ability to directly detect longer wavelength radio waves. And under normal circumstances, human eye are not aware of the existence of radio radiation. Therefore, a detector is used to convert radio waves into visible or audible forms. This instrument is called a radio telescope. The solar radio telescope is a typical radio telescope used to observe solar radio radiation. Among various celestial bodies, the sun is a body with strong radiation intensity. In the quiet state of the 2-10 GHz frequency band, the solar radio radiation flux density is about 30-200 SFU (1 SFU=1 × 10-22 W/Hz/m2). By using a solar radio telescope to observe the quiet and non explosive sun, students can intuitively understand the functions of the solar radio telescope, recognize the existence of radio waves, and understand the intensity and spectrum of solar radio radiation in a peaceful state.

(3) Lunar radio observation experiment

Observing the phases of the moon and understanding that different radio sources or influences from the sun result in different radiation intensities, it can promote students to understand the principles of radio observation. With the help of a solar radio telescope, the antenna system of the telescope can be controlled to track the moon in real time for observation. Through radio observations of the moon, radiation intensity and spectral images of typical frequency points at different periods of the moon can be obtained.

(4) Solar burst observation experiment

In high solar activity years, there is a significant amount of solar activity. By combining observation data from radio telescopes and data from domestic and foreign stations, the types of solar radio storms and their impact on the Earth can be understood. The experimental operation steps of the solar burst observation experiment are the same as those of the quiet solar radiation observation experiment [8].

(5) Experiment on antenna reception effect in space observation

As a sensor for solar radio, the antenna is an important sensitive device for many space environment detection. During the teaching process, it can gradually track and align with the sun, then gradually deviate from the sun, and further analyze the corresponding frequency data to deepen the understanding of the antenna.

Taking the observation experiment of electromagnetic radiation intensity in space background as an example, the experimental purpose, experimental instruments, supporting software and experimental process will be introduced. Other experiments are similar.

The purpose of the experiment is to understand the types and characteristics of electromagnetic radiation, as well as the impact of space electromagnetic environment on radio telescopes, then master the basic principles and methods of electromagnetic radiation observation, and further learn to use solar radio telescopes to observe electromagnetic radiation phenomena in space backgrounds. The solar radio telescope is the main instrument for observing the intensity of electromagnetic radiation in the space background, which can be used to receive and measure microwave radiation in space. The experimental supporting software is used to control and process radio observation data, which can process and analyze data, including ① antenna control software, which can be set to program control or manual control to achieve real-time tracking of the sun, ② data processing software with functions such as spectrum imaging display, radiation flow display, data calibration, storage control, judgment and reporting of solar radio bursts, as well as turntable control. The specific operation process of the experiment is as follows:

Step 1: Choose a period of good weather conditions, usually observe at the lowest point of solar activity;

Step 2: Check whether the equipment and instruments are normal, check the electrical connections to ensure the accuracy and reliability of the observation data;

Step 3: Start the solar radio telescope, open the control and display software of the upper computer, as shown in figure 4;

Step 4: Manipulate the antenna control system to align the antenna with the sky background, as shown in figure 5;

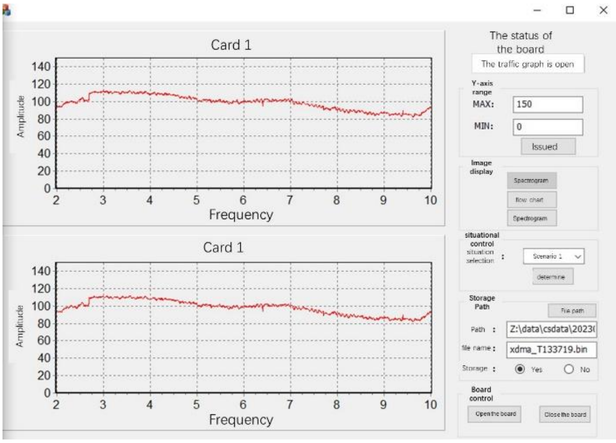

Fig. 4. Main page of upper computer software.

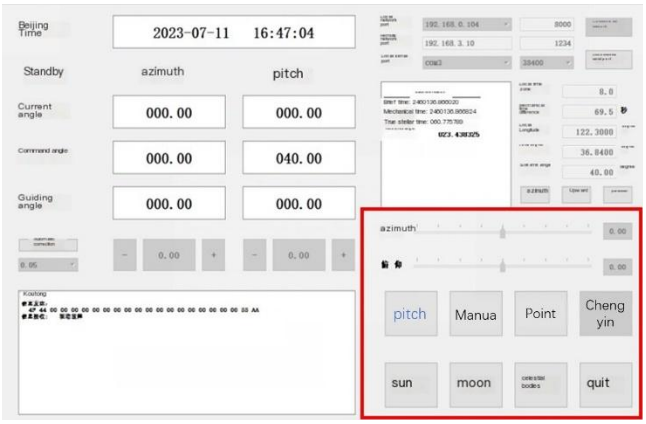

Fig. 5. Telescope control software.

Step 5: There are two ways to adjust the telescope's alignment with the sky: manual and pointing. In this experiment, manual adjustment is chosen. The operator can adjust the orientation and elevation angle of the telescope, continuously adjust the angle to point the telescope towards the sky, and be careful not to point towards the sun or be obstructed by tree floors. In the experiment, the operator can also choose the pointing method. This method requires clicking standby and then clicking pointing. The software will pop up a pointing adjustment interface. Adjust the telescope pointing by entering the orientation and elevation angle;

Step 6: Operate the upper computer control software to initialize and calibrate the solar radio telescope;

Step 7: Open the spectrum display interface and the radiation flow display interface of typical frequency points, observe the spectrum image and the radiation flow value of typical frequency points;

Step 8: When observing the spectral image of the sky background and the radiation flow value of typical frequency points, the antenna control system can be manipulated to align the antenna with different directions of the sky background, and conduct multi-directional spatial background electromagnetic radiation intensity observation. The antenna angle adjustment method is the same as above, and the spatial background electromagnetic radiation intensity data of multiple frequency points can be recorded;

Step 9: Compare and analyze the observation results with existing astronomical data to gain a deeper understanding of the electromagnetic radiation characteristics and laws of the spatial background.

5 Summary

This article constructs a teaching and experimental system for solar radio telescopes, which can monitor the spectrum and partial flow of solar radio signals in the 2-10 GHz frequency band in real time. The observation frequency band is wide, with good real-time performance and calibration function. This system has high time resolution and frequency resolution, and can achieve high-frequency and broadband signal data acquisition and processing of astronomical radio signals. In response to the teaching needs of space environment experiments, 5 experiments were conducted based on the solar radio telescope teaching experiment system, providing excellent experimental conditions for cultivating students' practical abilities. At present, software data processing, analysis, and display functions are relatively simple. In the future, software functions will be further enriched according to teaching and research needs.

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