Postprint: Automatic Electromagnetic Environment Spectrum Monitoring System with Self-Calibration

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Abstract

Pulsars are a class of neutron stars characterized by extremely stable rotation and emission of electromagnetic pulses. Three frontier fields of pulsar research necessitate that related radio astronomical observations require broader and more extensive radio frequency bands. The faint radio signals from deep space, combined with the high sensitivity of radio telescopes, render radio observations susceptible to electromagnetic interference from human activities, which can sometimes have devastating effects on radio observations; therefore, radio observations require site selection in locations with excellent electromagnetic environments. A monitoring system with triple calibration capability is constructed using broadband noise sources, 50 SZ matching loads, and high-low frequency antennas. The system is deployed at the Ailao Mountain Ecological Station to conduct observations across different frequency bands (100 MHz-18 GHz), multiple azimuth angles, two polarization angles, and under various climatic conditions. The methods for statistical analysis and processing of the observation data are described. The system can be widely applied to fields such as field electromagnetic environment monitoring and radio telescope site selection.

Full Text

A Self-Calibrating Automatic Electromagnetic Environment Spectrum Monitoring System

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Abstract

Pulsars are a class of neutron stars with extremely stable rotation that emit electromagnetic pulses. Current pulsar research fronts include discovering more pulsars, carefully studying known pulsars, and using them as probes to investigate gravitational waves and the interstellar medium. These research directions require radio astronomical observations to cover increasingly wider frequency bands. However, radio observations are susceptible to electromagnetic interference (RFI) from human activities due to the extremely weak deep-space radio signals and the high sensitivity of radio telescopes. Such interference can sometimes have fatal impacts on observations, necessitating that radio telescopes be sited in locations with excellent electromagnetic environments. This paper presents a monitoring system that employs a broadband noise source, 50 Ω matched load, and combined low/high frequency antennas to achieve triple calibration. The system was deployed at the Ailao Mountain Ecological Station in Jingdong County, Pu' er City, Yunnan Province, to conduct observations across different frequency bands (100 MHz–18 GHz), multiple azimuth angles, two polarization angles, and under various climatic conditions. We elaborate on the statistical analysis and processing methods for the observed data. This system can be widely applied to field electromagnetic environment monitoring and radio telescope site selection.

Keywords: Large Radio Telescope; Pulsars; Electromagnetic Interference; Self-Calibrating; Electromagnetic Environment

1. Introduction

Radio astronomy is a discipline dedicated to studying radio signals from deep space, with pulsar observations being particularly important. The current frontiers of pulsar research primarily involve three aspects: (1) discovering more pulsars, especially those with shorter periods and shorter orbital periods in binary systems; (2) using different methods to study known pulsars and investigate the physical characteristics and patterns of their radiation; and (3) employing pulsars as probes to detect interstellar medium, including interstellar electrons and magnetic fields, and to study gravitational waves [**?**]. Long-term monitoring of a set of millisecond pulsars can be used to define time standards, as their exceptionally stable rotation makes them the most precise clocks in the universe. The high stability and indestructible security of pulsars give them strategic application value, enabling autonomous navigation for interplanetary travel, which is of great significance for human space exploration. Once a set of high-precision pulsar ephemerides is established, pulsars can become beacons for interstellar travel. Currently, obtaining high-precision pulsar ephemerides mainly relies on ground-based observatories detecting radio emissions from pulsars and using multiple telescopes to quickly locate them and reduce arrival time residuals caused by position errors.

Radio signals from the universe are extremely weak. To detect these signals, radio telescopes must have large apertures and high sensitivity. While large apertures and high sensitivity provide advantages for radio observations, they also make the systems more susceptible to electromagnetic interference. RFI mainly includes electromagnetic emissions from artificial radio transmitters and receivers such as radio broadcasting, satellite communications, and WiFi. With the rapid development of information technology, an increasing number of radio frequency bands are being utilized, making frequency protection for radio astronomy increasingly challenging. According to the ITU Radio Regulations and the Regulations of the People' s Republic of China on Radio Frequency Allocation, the total bandwidth protected for radio astronomy is approximately 35 GHz. Benefiting from advances in computing, signal processing technology, and antenna technology, radio astronomy has detected more spectral lines outside the protected bands. Therefore, based on the characteristics of radio observations and the need to eliminate space-based RFI as much as possible, extremely strict requirements are imposed on the electromagnetic environment surrounding radio telescopes.

This paper utilizes self-calibration technology to design an automated method for radio environment measurement in the field, which is highly suitable for field radio environment measurement and site surveying for large radio telescopes. The system offers advantages such as simple installation, fully automated measurement, and convenient data management.

2. Impact of Radio Frequency Interference on Radio Observations

In radio astronomical observations, RFI impacts primarily include the following aspects. First, strong interference can cause receiver saturation. If electromagnetic interference within the observation band is too strong and exceeds the maximum input level of any stage in the analog receiver, the receiver becomes unable to detect any astronomical signals. Second, excessive RFI can produce spurious spectra. Due to limitations in the Fast Fourier Transform algorithm, the spectrum of interference signals can interact with the window function and the spectrum of astronomical signals, creating spectral interference that ultimately forms false spectral lines and results in an uneven noise floor. Third, multiple interference signals can generate intermodulation products of uncertain frequencies through interactions in the transmission medium, affecting the relative calibration of radio astronomical signals. This type of interference is unpredictable and difficult to filter using traditional methods. Fourth, interference signals can mix with local oscillator signals inside the receiver, creating modulation frequencies that fall within radio astronomy observation bands and affect the recovery and analysis of normal astronomical signals [?].

3. Electromagnetic Environment Monitoring System

3.1 System Architecture

The monitoring system consists primarily of hardware and software components. The hardware comprises an antenna module, broadband low-noise amplifier, antenna control module, and receiver module. Signals pass through a microwave switch that selects between the antenna, broadband noise source (used as a calibration source), and matched load. The selected signal is then processed by a broadband low-noise amplifier and converted to digital signals using a digital spectrum analyzer. The software is implemented using LabVIEW graphical programming and consists of two main modules: an antenna control module and a spectrum analyzer control program. The entire process configures the spectrum analyzer output, with subsequent data processing primarily based on these values. The system measures three values representing real-time, average, and maximum measurements for each frequency band. [Figure 1: see original paper] shows the system block diagram.

3.2 Equipment and Parameters

The system' s main equipment is divided according to measurement frequency band requirements into two types: 100 MHz–1 GHz and 1 GHz–18 GHz. The receiver module uses the Rohde & Schwarz FSU26 digital spectrum analyzer with an operating frequency of 20 Hz–26.5 GHz and an average noise level of -150 dBm. The antenna module uses HL223 and HL050 log-periodic antennas from Rohde & Schwarz. The HL223 antenna covers 100 MHz–1.3 GHz with a gain of 6–8 dBi, while the HL050 covers 0.85 MHz–26 GHz with a gain of 8–8.5 dBi. The microwave switch provides four-channel selection. The broadband low-noise amplifier uses the National Instruments DAQ 9171. details the parameters of the HL223 and HL050 log-periodic antennas.

The monitoring system' s original azimuth points toward true north to facilitate subsequent data processing. The monitoring approach is divided based on measurement frequency band and antenna half-power beamwidth. For the 100 MHz–1 GHz range using the low-frequency antenna, each 100 MHz sub-band is measured at four azimuth angles (0°, 90°, 180°, 270°) with both horizontal and vertical polarizations. Due to the high level of electromagnetic interference in this band that could cause saturation and measurement errors, no low-noise amplifier is used; instead, signals are fed directly to the digital spectrum analyzer. The spectrum analyzer sweep width is set to cover each sub-band, with display bandwidth and resolution bandwidth set to 30 kHz.

For the 1 GHz–3 GHz range, the spectrum analyzer sweep width is set to 250 MHz, covering multiple measurement sub-bands with display bandwidth and resolution bandwidth set to 20 kHz. The HL050 antenna is used for measurements in this band. For the 3 GHz–18 GHz range, the spectrum analyzer sweep width is set to 500 MHz, with display bandwidth and resolution bandwidth set to 30 kHz. Each sub-band covers both horizontal and vertical polarizations with an integration time of 600 seconds. The scanning process uses the microwave switch to sequentially connect the antenna, calibration noise source, and matched load to the system at six azimuth angles (0°, 60°, 120°, 180°, 240°, 300°) for the 1-3 GHz and 3-18 GHz bands.

4. Calibration Principles

4.1 Self-Calibration Methodology

This section introduces the calibration principles and main parameter calibration for the electromagnetic environment monitoring system. Self-calibration primarily employs two methods: direct measurement for the 100 MHz-1 GHz band where interference is strong, and the Y-factor method for the remaining bands. The main measurement process constitutes a calibration unit composed of a microwave switch, broadband noise source, and host computer.

Each measurement band observation is divided into three steps: (1) connect the antenna for one measurement, (2) connect the self-calibrating broadband noise source, and (3) connect the 50 Ω matched load. The noise source' s excess noise ratio is provided by the manufacturer and determined by real-time temperature monitoring at the site. The noise source power is read in real-time by the spectrum analyzer, and antenna gain is provided by Rohde & Schwarz. Based on these known quantities and microwave RF principles, system parameters such as gain and noise temperature after antenna connection can be obtained. With these parameters, the entire measurement process power can be converted to power spectral flux density based on the antenna' s effective area, yielding the electromagnetic environment conditions.

4.2 Parameter Calculations

The system must produce final data based on power spectral flux density for electromagnetic environment analysis. According to RF theory, parameters related to power spectral flux density include system power P, Boltzmann constant $k = 1.3806505(24) \times 10^{-23}$ J/K, system noise temperature, system gain G, and antenna effective area A.

System noise temperature and excess noise ratio are solved primarily using the hot/cold load method. To obtain the noise temperature when the noise source is active, the noise source' s excess noise ratio R is required, provided by the equipment manufacturer. The Y-factor is the ratio of spectrum analyzer measurements with the noise source connected (P_{EN}) to those with the matched load connected (P_L) [**?**]. The noise source temperature is $T_{EN} = T_0(1 + R)$, where T_0 is the local ambient temperature. Based on the relationship between gain and noise temperature, the spectrum analyzer' s observed power value can be expressed.

According to the three-step self-calibration process: - P_{ant} is the power spectral density measured by the spectrum analyzer after antenna connection - P_L is the power spectral density read after matched load connection - T_{ant} is the antenna temperature (i.e., the environmental temperature) - P_{EN} is the power spectral density after noise source connection - G is the system electrical gain excluding the antenna

The system noise temperature T_{sys} is the sum of antenna temperature and receiver temperature. Equations (4) through (7) can be derived directly from measurements [**?**].

In antenna theory, the effective area of an isotropic antenna is given by $A_{iso} = \lambda^2/4\pi$, where λ is the wavelength of the observation band. The monitoring system uses HL223 and HL050 log-periodic antennas with gains of 6-7 dBi for 100 MHz-1 GHz and 8-8.5 dBi for 1-18 GHz. The antenna effective area A is determined by $A = G\lambda^2/4\pi$ [**?**].

Power spectral flux density is defined as power per unit area per unit frequency. For the 3-18 GHz band, the system power spectral density measured by the spectrum analyzer after antenna connection is P_{sys} (W/Hz). Simultaneously, power spectral density can be expressed using antenna effective aperture area A and power spectral flux density Ψ as $P_{sys} = \Psi A$. The 100 MHz-1 GHz band uses direct measurement to determine power spectral flux density: $\Psi = P_{ant,total} - G_{cable} - G_{spec} - G_{ant} - 10\log B$, where $P_{ant,total}$ is the total power input to the spectrum analyzer after direct antenna connection, G_{cable} and G_{spec} represent signal amplification by the cable and spectrum analyzer internal components respectively, G_{ant} is the antenna gain, and B is the resolution bandwidth [**?**].

5. Field Measurements and Analysis

5.1 Measurement Site

The system was field-tested at the Ailao Mountain Ecological Station in Jingdong County, Pu' er City, Yunnan Province. The ecological station, established by the Xishuangbanna Branch of the Yunnan Botanical Garden of the Chinese Academy of Sciences, is far from urban centers and has an excellent electromagnetic environment, making it an outstanding candidate site for a large radio telescope.

Data processing primarily involves calculating the power spectral flux density for each frequency band and azimuth angle, with results compiled into graphical representations for sequential analysis.

5.2 Measurement Results

For the 100 MHz-1 GHz band, direct measurement yields a power spectral flux density of approximately -195 dB(W/m²/Hz). Interference signals exceeding the average spectral flux density by 5-10 dB are primarily identified at 470 MHz (China Telecom) and 800 MHz (rural satellite TV). The ITU-allocated primary service bands for radio astronomy at 322–328.6 MHz, 606–610 MHz, and 610–614 MHz show no interference [?]. [Figure 2: see original paper] shows the power spectral flux density for horizontal polarization at 0° azimuth in the 100 MHz–700 MHz range, while [Figure 3: see original paper] covers 700 MHz–1 GHz at the same orientation.

For the 1-3 GHz band measured using the calibration method, the power spectral flux density is approximately -210 dB(W/m²/Hz). Signals exceeding the average by 8–13 dB are mainly aviation navigation at 1.7 GHz and China Mobile at 2.4 GHz (Bluetooth and workstations). The ITU-allocated bands at 1400–1427 MHz, 1610.6–1613.8 MHz, 1660.5–1670 MHz, and 2655–2700 MHz show no interference [?]. [Figure 4: see original paper] presents the power spectral flux density for horizontal polarization at 0° azimuth.

For the 3-18 GHz band, also using the calibration method, the power spectral flux density is approximately -205 dB(W/m²/Hz). Signals exceeding the average by 3–5 dB are primarily satellite communication at 3.8 GHz, radio location at 5.7 GHz, and satellite fixed services at 10.7 GHz. The ITU-allocated radio service band at 4800–5000 MHz shows no interference [?], though weak interference appears at 15.35–15.4 GHz. [Figure 5: see original paper] shows vertical polarization at 120° azimuth for 1–3 GHz, and [Figure 6: see original paper] shows vertical polarization at 120° azimuth for 3–18 GHz.

6. Conclusion

Given the station' s geographic location, it can monitor pulsars north of certain latitudes, covering a significant portion of known pulsars and observable sky area. This observatory base can clearly become an indispensable monitoring facility for breakthroughs in pulsar astronomy and pulsar discovery programs. Furthermore, the above analysis demonstrates that the site is far from human activity, experiences minimal interference, and the interference signals that do appear are identifiable and can be mitigated. For instance, signals from the ecological station can use wired connections, and known interference sources can be avoided. The site experiences weak radio interference from tourism development and other activities, particularly in the 1-3 GHz band. Therefore, Ailao Mountain Station, with its unique geographic environment and status as a botanical garden ecological reserve, represents an excellent location for establishing a large radio telescope for applications such as gravitational wave detection and pulsar radiation research.

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