A novel low frequency radio astronomical observation array(1 90MHz) and its first light postprint

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Abstract

The extremely low frequency (f<40MHz) is a very important frequency band for the modern radio astronomy observations. It is also a key frequency band for solar radio bursts, planetary radio bursts, fast radio bursts detected in the lunar space electromagnetic environment and the Earth's middle and upper atmosphere with low dispersion values. In this frequency band, the solar stellar activity, the early state of the universe, and the radiation characteristics of planetary magnetosphere and plasma layer can be explored. Since there are few observations with effective spatial resolution in extremely low frequency, it is highly possible to discover unknown astronomical phenomena on such band in the future. In conjunction with low frequency radio observation on the far side of the Moon, we initially set up a novel low-frequency radio array in the Qitai Observation Station of Xinjiang Astronomical Observatory deep in Tianshan Mountains, Xinjiang, China on August 23, 2021. The array covers an operating frequency range of 1~90MHz with a sensitivity of -78dBm/125kHz, a dynamic range of 72dB, and a typical gain value of 6dBi, which can realize unattended all-weather observations. The two antennas (1~62MHz) due south of the Qitai Low-Frequency Radio Array (Qitai LFRA) were put into trial observations on May 28, 2021, and the very quiet electromagnetic environment of the station has been confirmed. So far, many solar radio bursts and other foreign signals have been detected. The results show that this novel low frequency radio array has the advantages of good performance, strong direction and high antenna efficiency. It can play a unique role in Solar Cycle 25, and has potential value in prospective collaborative observation between the Earth and space for the extremely low frequency radio astronomy.

Full Text

Preamble

A Novel Low-Frequency Radio Astronomical Observation Array (1–90 MHz) and Its First Light

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Abstract

The extremely low frequency band (f < 40 MHz) represents a critically important region for modern radio astronomy observations. This band is essential for studying solar radio bursts, planetary radio emissions, fast radio bursts detected in the lunar space electromagnetic environment, and Earth's middle and upper atmosphere with low dispersion measures. This frequency range enables exploration of solar-stellar activity, the early state of the universe, and the radiation characteristics of planetary magnetospheres and plasma layers. Since few observations have achieved effective spatial resolution at extremely low frequencies, this band holds high potential for discovering unknown astronomical phenomena in the future. In conjunction with low-frequency radio observations from the far side of the Moon, we established a novel low-frequency radio array at the Qitai station of Xinjiang Astronomical Observatory, located deep in the Tianshan Mountains of Xinjiang, China, on August 23, 2021. The array covers an operating frequency range of 1–90 MHz with a sensitivity of –78 dBm/125 kHz, a dynamic range of 72 dB, and a typical gain of 6 dBi, enabling unattended all-weather observations. Two antennas facing due south of the Qitai Low-Frequency Radio Array began trial observations on May 28, 2021, confirming the station's exceptionally quiet electromagnetic environment. To date, numerous solar radio bursts and other signals have been detected. These results demonstrate that this novel low-frequency radio array offers excellent performance, strong directionality, and high antenna efficiency. It can play a unique role during Solar Cycle 25 and holds potential value for prospective collaborative observations between Earth and space for extremely low-frequency radio astronomy.

Key words: extremely low frequency; solar radio burst; Qitai Low-Frequency Radio Array

1 INTRODUCTION

Radio technology in the radio waveband did not truly develop until the 1940s. In the late 1940s, many radar systems originally used for military surveillance were repurposed as astronomical telescopes by radio scientists for low-frequency radio observations, particularly in Britain, France, and Australia. During this period, ground-based low-frequency radio observations entered a stage of vigorous development (Boonstra et al. 2016; Orchiston et al. 2010). Since 1958, a series of low-frequency radio arrays had been established in Australia (Orchiston et al. 2015; George et al. 2015). These low-frequency antennas yielded considerable scientific achievements, including the discovery of Jupiter's radio eruptions, the first extremely low-frequency radio contour map of the Milky Way (Cane et al. 1977), and mapping of the Moon's uneven surface topography. Notably, pulsars, quasars, cosmic microwave background radiation, and interstellar organic molecules—known as the four major astronomical discoveries of the 1960s—were all based on radio astronomical observations. These remarkable discoveries laid the foundation for subsequent developments in low-frequency radio astronomy. By the 1990s, many low-frequency radio antennas were capable of making high-resolution observations targeting Earth's magnetosphere, the cislunar environment, solar radio emissions, galaxies, quasars, and other phenomena.

Since the 21st century, rapid advancements in science and technology have dramatically improved computer data processing speeds and capabilities, enabling significant progress across various disciplines. Consequently, low-frequency radio astronomy has entered an unprecedented stage of rapid development. Low-frequency radio observations can be conducted through three primary methods: ground-based observations, space-based observations, and lunar low-frequency radio detection (Mei et al. 2018). On January 3, 2019, China's Chang'e-4 satellite, equipped with an extremely low-frequency radio spectrometer (Zhang et al. 2019) operating at 0.1–40 MHz, successfully achieved a soft landing on the far side of the Moon, marking a breakthrough in China's lunar-based low-frequency radio detection. Considering factors such as construction period, maintenance, and operational costs, ground-based low-frequency radio observation is clearly the most economical approach compared to space and lunar observations. However, due to the natural high-pass filter effect of Earth's ionosphere, meter-wave signals (10–40 MHz) reaching the Earth's surface are severely distorted. The ionospheric cutoff frequency (approximately 10 MHz) depends on ionospheric characteristics, with lower atmospheric ionization facilitating electromagnetic wave propagation to the surface. To obtain effective data, ground-based low-frequency radio telescopes must avoid ionospheric effects, making telescope location one of the most critical factors affecting extremely low-frequency radio observations (George et al. 2015). The lowest degree of ionospheric ionization occurs in mid-latitude regions at a certain distance from geomagnetic poles—the ionospheric trough region (He et al. 2011). These areas represent relatively ideal locations for extremely low-frequency radio observations. Additionally, expanding interferometric array size, seeking international cooperation, and combining ground-based low-frequency radio antennas with space satellites and lunar low-frequency radio scientific equipment for joint observations can achieve detection capabilities with lower frequency limits, higher sensitivity, and higher resolution. Table 1 lists representative domestic and international low-frequency instruments (or stations) and their parameters (Ellingson et al. 2009; van Haarlem et al. 2013; Chen et al. 2021; Peng et al. 2017; Zhao et al. 2022; Xu. 2022; Zhong et al. 2016; Dong. 2022; Lu et al. 2022).

The remainder of this paper is organized as follows: Section 2 introduces the site selection and construction of the Qitai Low-Frequency Radio Array (Qitai LFRA), the basic working principles of the observation system, and relevant tests of the low-frequency radio array. Section 3 presents system debugging procedures and observation results of solar radio bursts captured by the array. The final section provides conclusions and future prospects.

2.1 The Site Selection and Construction

Meteorological conditions, radio environment, geographical location, geological features, and basic infrastructure (roads, water, electricity, communications) are all key considerations for radio telescope siting (Wang. 2014). Qitai station is located at the northern foot of the Tianshan Mountains, approximately 260 kilometers from Urumqi, within a basin measuring about 1.5 kilometers east-west and 2 kilometers north-south, at an altitude of 1730–1830 m. The station is surrounded by mountain ridges at approximately 1,900 meters altitude, providing an enclosed environment that helps reduce radio frequency interference. Additionally, Qitai station will host the 110-meter-aperture radio telescope (Qitai Radio Telescope, QTT) currently under construction.

Based on QTT site selection data, Qitai station is a basin with higher elevation in the southeast and lower in the northwest, featuring good sealing and isolation from surrounding areas. Peripheral radio applications primarily include mobile wireless communications (UHF, L, S bands), broadcast television (analog and digital) (VHF, UHF bands), and satellite TV wireless differential systems (UHF, C band) (Wang. 2014). Radio interference detected by the automatic radio environment measurement system for the QTT site (monitoring frequency: 80 MHz–12 GHz) is mainly concentrated in the 410–1000 MHz band (Liu. 2017; Liu et al. 2019). Furthermore, Qitai station's basic infrastructure, geological, and meteorological conditions fully meet site selection requirements. Generally speaking, Qitai station is far from urban areas, and the basin terrain provides some electromagnetic shielding, which is conducive to long-term radio environmental protection. It is an excellent site for astronomical observation, as shown in Figure 1 [Figure 1: see original paper].

Following field investigations at Qitai station, the Qitai LFRA construction site was finally determined to be approximately 100 meters south of the wind tower in the park, at a geographical position of 43°36 north latitude and 89°41 east longitude. This mid-latitude area has an altitude of 1,675.90 meters, as shown in Figure 2 [Figure 2: see original paper]. Construction of Qitai LFRA began in October 2020 and was initially completed on August 23, 2021. The construction work mainly included antenna pier processing, equipment room fabrication, power supply cable laying, antenna main structure erection, and antenna array installation. Using the constructed log-periodic antenna, we monitored the nearby radio environment (test frequency band: 1–60 MHz) and found that interference signals in this area are mainly concentrated below 20 MHz, while the frequency band above 20 MHz is relatively clean. The power of interference signals is approximately –50 to –60 dBm/15 kHz, reaching –47 dBm/15 kHz at 11.6 MHz, whereas signal power above 20 MHz is approximately –110 to –120 dBm/15 kHz—a difference of about 60 dB. Considering these factors, we will focus future detection targets on frequencies above 20 MHz. The monitoring results are shown in Table 2 .

2.2 Antenna Introduction

The antenna (design frequency: 1–90 MHz) is designed and fabricated as a medium-gain system. Due to budget constraints, the corresponding receiver (observation frequency: 1–62 MHz) is primarily used for solar radio signal reception in the first stage, with subsequent expansion to cover all bands. For the medium and low-gain components, our future observation frequency target will extend to approximately 210 MHz. Qitai LFRA consists of eight antennas whose main function is to capture, select, and amplify signals. The antenna structure is a log-periodic design, which offers wide bandwidth, simple structure, and light weight (He et al. 2021). In Figure 3 [Figure 3: see original paper], the black blocks represent antenna base piers, with one antenna mounted on every three base piers, totaling 24 base piers. A column on each base pier supports the antenna, with a mounting plate between the column and antenna main rod connected and secured by screws. All antennas are distributed in a circle with an 11-meter radius. The antennas facing due south are labeled No. 1 and No. 2, with other antennas labeled sequentially in a similar manner.

The primary scientific objective of Qitai LFRA is monitoring radio emissions from the Sun and planets in the solar system. Therefore, the angle between the LFRA direction and the horizontal plane must be precise to ensure targets fall within the antenna's main beam. Qitai LFRA also has the capability to observe electromagnetic signals from other stars. For this purpose, eight differently-pointing antennas have been arranged to expand the observation range and cover the entire sky. Qitai LFRA is situated on a ridge with wide, flat north-south terrain and narrow, sloping east-west terrain. Considering these terrain characteristics and the fact that scientific observation targets are primarily concentrated in the north-south direction, the eight antennas are arranged on a circular plane at specific angles, as shown on the left side of Figure 3. Additionally, according to scientific research needs, any two adjacent antennas can be selected to simultaneously detect celestial bodies, demonstrating Qitai LFRA's operational flexibility. Specific performance indicators for each antenna are shown in Table 3 . Antennas 1 and 2 are primarily used for coordinated observations with the Chang'e-4 low-frequency radio antenna on the far side of the Moon (Ji et al. 2017).

Figure 4 [Figure 4: see original paper] shows the site map of Qitai LFRA, where the white house is the equipment room and the direction of the highest wind tower indicates due north.

2.3 The S11 Parameters Measurement of the Antenna

A portable vector network analyzer (NanoVNA V2) is a popular tool for measuring antenna parameters. It can measure the S11 parameter, which represents the antenna's reflection coefficient. Figure 5 [Figure 5: see original paper] shows the measurement results for antenna 1's S11 parameter, where the red curve represents return loss measurement results, indicating the amount of power reflected back by the antenna. The blue curve represents standing wave ratio (SWR) measurement results, indicating how well the antenna matches the impedance of its transmission line. The horizontal axis represents the measured frequency range (10–90 MHz). The left vertical axis shows return loss (dB), while the right vertical axis shows standing wave ratio. During field measurements, external signals received by the antenna can influence measurement results, causing some discrepancy between actual and theoretical measurements. The figure shows that standing wave measurements below 20 MHz are poor, likely due to external interference signals.

2.4 Observation System

The observation system has a sensitivity of –78 dBm/125 kHz, a maximum signal power amplitude of –6 dBm, and a dynamic range of 72 dB. It includes two groups of log-periodic antennas, corresponding analog signal front-end filter and amplification modules, an ADC (Analog-to-Digital Converter) acquisition card, digital signal processing module, host computer processing and display, data storage, and other components (Xu et al. 2023), as shown in Figure 6 [Figure 6: see original paper].

The system operates as follows: Antennas receive low-frequency signals from the sky. After initial amplification and frequency selection, signals are transmitted via cable to the analog front end. The analog front end first combines four channels into two signals, then amplifies and filters them, finally outputting signals with appropriate frequency and power for ADC collection. After receiving these signals, the acquisition card performs digital signal processing; the FPGA (Field-Programmable Gate Array) processes signals in real time before encapsulating and storing the data. The host computer can perform frequency-domain and time-domain switching, select accumulation times, choose clock sources, and specify plotting and storage paths. GNSS (Global Navigation Satellite System) antennas receive satellite signals and feed them to the rubidium clock, which synchronizes time and provides timestamps to the digital signal processing unit. For large data volumes, a disk array server can store the data. Additionally, remote control and data file transmission can be achieved through Internet connectivity. The main performance parameters of the observation system are shown in Table 4 .

2.5 Observation Equipment

The observation equipment is housed in a simple 18-square-meter room and consists of a regulated power supply, analog front end, ADC acquisition and digital signal processing unit, rubidium clock, disk array, network switch, and GNSS time-frequency receiver, as shown in Figure 7 [Figure 7: see original paper]. The rubidium atomic clock provides time-frequency reference and synchronized time information after training. Disk arrays store observation data transmitted from digital terminals through high-speed optical fibers in real time. Once all observation equipment is operational, no on-site observers are required; remote login can be used for monitoring and debugging. Additionally, observers visit the station regularly to back up observation data and perform equipment overhaul and maintenance.

3.1 System Debugging and Trial Observation

The two antennas facing due south of Qitai LFRA officially entered the system debugging and trial observation phase on May 28, 2021. The 16-bit ADC successfully collected and recorded signals with a large dynamic range; however, during the trial observation phase, the system received numerous interference signals in addition to local fixed broadcast signals. As shown in Figure 8 [Figure 8: see original paper], the left and right images correspond to Channel 1 (vertical polarization) and Channel 2 (horizontal polarization), respectively. Finally, by removing the first-stage analog amplifier in Channel 2 (30 dB) and adding a high-pass filter (~25 MHz) in Channel 1, most interference signals were eliminated, yielding a very clean background signal (see Figure 9 [Figure 9: see original paper]). Subsequent observations confirmed these adjustments were highly effective. After modification, Channel 1 achieved higher sensitivity detection capability for signals above 20 MHz, while Channel 2 retained detection capability for high-power signals as low as 1 MHz.

3.2 Event Example

At approximately 08:34:10 UT on July 16, 2021, Qitai LFRA detected a solar radio burst event (Wang et al. 2023) for the first time, with frequency coverage of 10–62 MHz and duration of about 2 minutes. This radio burst exhibited the fundamental characteristics of type III solar radio bursts—a rapid frequency drift phenomenon—with certain fine structures and J-type features, as shown in Figure 10 [Figure 10: see original paper]. The fine structure of type III solar radio bursts can be used to diagnose coronal parameters such as electron density, energetic electron velocity, and coronal atmospheric turbulence, as well as to predict space weather (Tan et al. 2021; Feng et al. 2021). This observed solar radio burst coincided with solar X-ray bursts monitored by the National Oceanic and Atmospheric Administration (NOAA), as shown in Figure 11 [Figure 11: see original paper].

At approximately 06:20 UT on September 28, 2021, Qitai LFRA detected a type II solar radio burst event for the first time (Yang et al. 2023), with frequency coverage of 18–50 MHz, duration exceeding 10 minutes, and exhibiting typical slow frequency drift and band splitting, as shown in Figure 12 [Figure 12: see original paper]. Preliminary calculations indicate the type II radio burst's fundamental frequency structure drifted at approximately –0.04 MHz/s. Combined with the Newkirk coronal density model (Smerd et al. 1975), the CME (Coronal Mass Ejection) shock velocity is calculated to be about 500 km/s, which is basically consistent with the CME shock velocity (524 km/s) detected by the SOHO (Solar and Heliospheric Observatory) coronagraph at the same time. Additionally, Qitai LFRA observed the radiation band structure of type II radio bursts in the horizontal polarization band below 25 MHz, further demonstrating the array's capability to detect lower-frequency signals. Currently, Qitai LFRA's back-end equipment can receive signals from at most two antennas; we will configure new equipment in later stages to enable scientific observations across the entire sky.

4 CONCLUSIONS AND PROSPECTS

The development of low-frequency radio astronomy is closely related to advances in science and technology. With rapid progress in space technology, increasingly weak very low-frequency radio signals have been obtained; however, ground-based low-frequency radio observations remain a very important and indispensable component. By employing all-sky, medium-gain, synchronous observation techniques, and with the aid of interferometry technology similar to remote equipment, we can better suppress artificial noise and more sensitively extract radiation signals generated by celestial bodies in this frequency band.

Observations from Qitai LFRA demonstrate that the array features lower detection frequency limits, better time and frequency resolution, high sampling accuracy, high sensitivity, large sky coverage, and flexible observation capabilities. It offers significant advantages in the field of low-frequency radio observation both domestically and internationally, particularly in the 1–40 MHz range.

In the future, we plan to construct arrays similar to Qitai LFRA in other areas of Xinjiang and implement joint observations by grouping these arrays to further improve observation resolution. We believe it is highly possible to detect unknown astronomical phenomena in this frequency band and expect to make important scientific discoveries using the Qitai LFRA platform to fill the gap in exploration of the very low-frequency radio band.

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