

A Novel Low-frequency Radio Astronomical Observation Array (1–90 MHz) and its First Light (Postprint)

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Abstract

The extremely low frequency ($f < 40$ MHz) is a very important frequency band for 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 the planetary magnetosphere and plasma layer can be explored. Since there are few observations with effective spatial resolution in the extremely low frequency, it is highly possible to discover unknown astronomical phenomena on such a 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 station of Xinjiang Astronomical Observatory deep in Tianshan Mountains, Xinjiang, China on 2021 August 23. The array covers an operating frequency range of 1–90 MHz with a sensitivity of -78 dBm/125kHz, a dynamic range of 72 dB, and a typical gain value of 6 dBi, which can realize unattended all-weather observations. The two antennas due south of the Qitai Low-Frequency Radio Array were put into trial observations on 2021 May 28, 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 a potential value in prospective collaborative observation between the Earth and space for extremely low frequency radio astronomy.

Full Text

Preamble

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A Novel Low-frequency Radio Astronomical Observation Array (1–90 MHz)
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Abstract

The extremely low frequency band ($f < 40$ MHz) is critically important 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 values. In this frequency range, researchers can investigate 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, the likelihood of discovering unknown astronomical phenomena in this band remains high. 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, deep in the Tianshan Mountains of Xinjiang, China, on 2021 August 23. The array covers an operating frequency range of 1–90 MHz with a sensitivity of -78 dBm/125kHz, 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 2021 May 28, confirming the station's exceptionally

quiet electromagnetic environment. To date, numerous solar radio bursts and other signals have been detected. The results demonstrate that this novel low-frequency radio array offers excellent performance, strong directivity, and high antenna efficiency. It can play a unique role in Solar Cycle 25 and holds potential value for prospective collaborative observations between Earth and space for extremely low-frequency radio astronomy.

Key words: The Sun – Astronomical Instrumentation – Methods and Techniques – Stars – Planetary Systems

1. Introduction

Radio technology in the radio wave band 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 (Orchiston & Sullivan 2010; Boonstra et al. 2016). Since 1958, a series of low-frequency radio arrays have been established in Australia (George et al. 2015; Orchiston et al. 2015), yielding considerable scientific achievements such as the discovery of Jupiter’s radio eruptions, the first extremely low-frequency radio contour map of the Milky Way (Cane & Whitham 1977), and mapping of the Moon’s uneven surface topography using these low-frequency antennas. 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.

In the 1990s, many low-frequency radio antennas became capable of high-resolution observations, with targets spanning Earth’s magnetosphere, the cislunar environment, solar radio emissions, galaxies, and quasars. Since the 21st century, rapid advancements in science and technology, particularly in computer data processing speed and capability, have enabled significant progress across various disciplines. Consequently, low-frequency radio astronomy has entered an unprecedented stage of rapid development. There are roughly three methods for low-frequency radio observations: ground-based observations, space-based observations, and lunar low-frequency radio detections (Mei et al. 2018).

On 2019 January 3, China’s Chang’e-4 satellite, equipped with an extremely low-frequency radio spectrometer (operating frequency: 0.1–40 MHz) (Zhang & Su 2019), 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 periods, maintenance, and operational costs, ground-based low-frequency radio observations are clearly the most economical approach compared to space and lunar observations. However, due

to the presence of a natural high-pass filter—Earth’s ionosphere—meter-wave signals (10–40 MHz) reaching the Earth’s surface are severely distorted. The ionosphere’s cutoff frequency (approximately 10 MHz) depends on its characteristics, with lower atmospheric ionization allowing easier transmission of electromagnetic waves to Earth. To obtain effective data, ground-based low-frequency radio telescopes must minimize ionospheric effects, making telescope location a critical factor for extremely low-frequency radio observations (George et al. 2015). The lowest degree of ionospheric ionization occurs in the mid-latitude region at a certain distance from geomagnetic poles, known as the ionospheric trough or ionospheric hole 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 equipment for joint observations can achieve detection capabilities with lower frequencies, higher sensitivity, and higher resolution.

Table 1 lists representative low-frequency instruments (or stations) and their parameters both domestically and internationally (Ellingson et al. 2009; van Haarlem et al. 2013; Han et al. 2016; Peng et al. 2017; Chen et al. 2021; Dong 2022; Lu et al. 2022; Xu 2022; Zhao 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 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

Radio telescope siting requires careful consideration of meteorological conditions, radio environment, geographical features, and infrastructure (roads, location, geology, water, electricity, communications) (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 1900 m altitude, providing an enclosed environment that helps reduce radio frequency interference. Qitai station is also the site of 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, offering 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 at

the QTT site (monitoring frequency: 80 MHz–12 GHz) is mainly concentrated in the 410–1000 MHz frequency range (Liu 2017; Liu et al. 2019). Additionally, Qitai station’s infrastructure, geological, and meteorological conditions fully meet site selection requirements. Overall, Qitai station’s remote location from urban areas and the basin terrain provide effective electromagnetic shielding, creating favorable conditions for long-term radio environmental protection and making it an excellent site for astronomical observations, as shown in Figure 1 [Figure 1: see original paper].

Following field investigations, the Qitai LFRA construction site was finalized approximately 100 m 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 m, as shown in Figure 2 [Figure 2: see original paper]. Construction of Qitai LFRA began in 2020 October and was initially completed on 2021 August 23. The construction work primarily included antenna pier fabrication, equipment room construction, power supply cable installation, and equipment 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 interference signal power at 11.6 MHz can reach -47 dBm/15 kHz, whereas signals above 20 MHz have power levels of approximately -110 – -120 dBm/15 kHz—a difference of about 60 dB. Based on these results, we will focus future detection efforts 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 for medium gain operation. Due to budget constraints, the corresponding receiver (observation frequency: 1–62 MHz) is primarily used for solar radio signal reception in the initial stage, with subsequent expansion to cover all bands. For medium and low gain components, our future observation frequency target will be 210 MHz. Qitai LFRA consists of eight antennas whose main functions are signal capture, frequency selection, and amplification. The antenna structure is a log-periodic design, which offers a wide frequency band, simple structure, and lightweight characteristics (He & Zhang 2021). In Figure 3 [Figure 3: see original paper], black blocks represent antenna base piers, with one antenna mounted on every three base piers, totaling 24 base piers. Columns on the base piers support the antennas, with mounting plates between the columns and antenna main rods connected and secured by screws. All antennas are distributed in a circle with a radius of 11 m. The antennas in the due-south direction 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 are

within the antenna's main beam. Qitai LFRA also has the task of observing electromagnetic signals from other stars. To this end, eight antennas with different pointings 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 for simultaneous celestial body detection, demonstrating Qitai LFRA's operational flexibility. The 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 represents the equipment room and the direction of the highest wind tower is due north.

2.3. The S11 Parameter Measurement of the Antenna

A portable vector network analyzer (NanoVNA V2) is a popular tool for measuring antenna parameters, capable of measuring the S11 parameter, which represents the antenna's reflection coefficient. Figure 5 [Figure 5: see original paper] shows the measurement results of antenna 1's S11 parameter, where the red curve represents return loss measurements (the amount of power reflected back by the antenna) and the blue curve represents standing wave ratio (SWR) measurements (how well the antenna matches the impedance of the connected transmission line). The horizontal coordinate ranges from 10 to 90 MHz, the left vertical axis shows return loss (dB), and the right vertical axis shows SWR. During field measurements, external signals received by the antenna can influence measurement results, causing some discrepancy between actual antenna measurements and theoretical frequency response. The figure shows poor standing wave measurement performance below 20 MHz, likely caused by 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. The system includes two groups of log-periodic antennas, corresponding front-end filter and amplification modules for analog signals, an ADC (Analog-to-Digital Converter) acquisition card, a digital signal processing module, upper computer processing and display, and data storage (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 chan-

nels into two signals, then amplifies and filters them, finally outputting signals with appropriate frequency and power for ADC acquisition. The FPGA (Field-Programmable Gate Array) performs real-time digital signal processing, then encapsulates and stores the data. The upper computer can switch between frequency and time domains, select accumulation times, choose clock sources, and specify drawing 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 the Internet network. 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]. A 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, as remote login enables monitoring and debugging. 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 due-south antennas of Qitai LFRA officially entered the system debugging and trial observation phase on 2021 May 28. The 16-bit ADC successfully collected and recorded signals with a large dynamic range; however, during trial observations, the system received numerous interference signals in addition to local fixed broadcast signals, as shown in Figure 8 [Figure 8: see original paper], with the left and right panels showing Channel 1 (vertical polarization) and Channel 2 (horizontal polarization), respectively.

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 2021 July 16, Qitai LFRA detected its first solar radio burst event (Wang et al. 2024) with frequency coverage of 10–62 MHz and a duration of about 2 minutes. This radio burst exhibits the fundamental characteristic of type III solar radio bursts—rapid frequency drift—with certain fine structures and J-type features, as shown in Figure 10 [Figure 10: see original paper]. The fine structures 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 (Feng & Zhao 2021; Tan 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 2021 September 28, Qitai LFRA detected its first type II solar radio burst event (Yang et al. 2023), with frequency coverage of 18–50 MHz, duration exceeding 10 minutes, and exhibiting typical slow frequency drift and band-splitting structures of type II radio bursts, as shown in Figure 12 [Figure 12: see original paper]. Preliminary calculations indicate a frequency drift rate of approximately -0.04 MHz s^{-1} . 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^{-1} , which is basically consistent with the CME shock velocity (524 km s^{-1}) 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 its 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 the future to enable scientific observations across the entire sky.

4. Conclusions and Prospects

The development of low-frequency radio astronomy is closely tied to scientific and technological progress. With rapid advancements in space technology, an increasing number of weak very low-frequency radio signals have been obtained, yet ground-based low-frequency radio observations remain a crucial and indispensable component. By employing all-sky, medium-gain, synchronous observation techniques, and leveraging 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.

Qitai LFRA’s observation results demonstrate characteristics including lower detection frequency, 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 very low-frequency radio bands.

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