Radio astronomy observation on distributed deep space radar: A prototype experiment Postprint

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Abstract

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Full Text

Preamble

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Radio Astronomy Observation on Distributed Deep Space Radar: A Prototype Experiment

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Abstract: Earth-based deep space radar studies celestial bodies by both transmitting and receiving radio waves, whereas radio telescopes only work passively. On the operational level, radar missions use only short observation times, which leaves a large portion of the time available for astronomical observations. However, the design principles used for radar and radio telescopes differ. Technical challenges are involved in making the instruments required to meet the requirements of these two applications simultaneously. In this study, we have attempted to tune a deep space radar system for use in radio astronomical applications and conducted a successful pulsar observation, thus demonstrating the feasibility of using radar systems, particularly distributed deep space radar, to perform astronomical research. Additionally, given the limited astronomical capacity available within the observed frequency range, this system has the potential to contribute to the long-term monitoring of specific radio sources. This work represents the first successful attempt to use an Earth-based deep space radar system to perform radio astronomy in China. We also discuss the challenges of tuning a built radar system for astronomical observation applications and propose recommendations for the design of future large-scale distributed deep space radar systems with innate astronomical capabilities.

Keywords: Radar telescopes; Ground telescopes; Radio observation

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1. Introduction

Radar astronomy and radio astronomy are scientific fields that both use radio waves to study celestial bodies, but they differ in terms of their methods, technologies, and research targets. Radio astronomy primarily involves the reception of radio waves emitted by celestial sources, including stars, galaxies, pulsars, and nebulae. In addition to these natural light sources, radio astronomy also deals with artificial radio signals, including those transmitted by spacecraft, which are used in various planetary science applications[1]. In contrast, radar astronomy involves active transmission of radio waves toward celestial bodies and analysis of the reflected signals, primarily for investigation of solar system targets, e.g., planets, asteroids, and comets. Radar astronomy is able to provide detailed surface imagery and highly accurate distance and velocity measurements.

Both radar and radio astronomy share multiple similarities in their observational equipment, including the use of large antennas and high-sensitivity receivers. Some observatories were originally designed as radio telescope facilities but were later upgraded with radar transmission capabilities. One example is the Arecibo Observatory[2], which was initially designed to study the ionosphere. However, because of a combination of technological advancements and changing scientific needs, a transmitter was added, thus enabling it to function as both a radio telescope and a radar system. Similarly, the Green Bank Telescope (GBT), which is one of the largest fully steerable radio telescopes worldwide, is currently undergoing modifications and has partially implemented radar transmission capabilities as part of its next-generation high-power planetary radar system[3]. Under the Next-Generation Radar[4],[5] initiative, the GBT is expected to support planetary radar observations while also maintaining its role as a premier radio astronomical instrument.

In contrast, several facilities were originally designed as radar systems but were later used to perform radio astronomical observations. One example is the Haystack Observatory, which was initially developed as a space surveillance radar. Over time, this observatory has been used to perform radio astronomical studies, including monitoring of quasars and participation in the Event Horizon Telescope (EHT) project[6]. The Goldstone Solar System Radar (GSSR)[7−9] is another radar facility that has also supported radio astronomy. The GSSR was primarily used for imaging of near-Earth asteroids and planetary surfaces. Its 34 m DSS-12 antenna has also been repurposed for use in educational and scientific radio astronomy projects under the Goldstone-Apple Valley Radio Telescope (GAVRT) program[10]. Similarly, the former Soviet Union’ s Evpatoria RT-70 offers an additional example of this dual-use approach[11]. Several tracking and control antennas in China have been modified for pulsar observations, including the 66 m antenna at the Jiamusi Deep Space Tracking Station[12]. However, no Earth-based radar system in China has been used to perform radio astronomical observations to date.

When compared with other domestic radio telescopes, e.g., the Five-hundredmeter Aperture Spherical Radio Telescope (FAST)[13],[14], distributed Earth-based radar systems offer complementary capabilities, including different radio observation frequencies and flexible antenna configurations. We modified one Earth-based radar system for use in astronomical observations without affecting its routine usage and conducted a pulsar observation experiment. This marks the first instance of use of an Earth-based radar system for radio astronomy in China and demonstrates the feasibility of radar-based radio astronomy applications. Although the modification of the radar system, because of its design differences when compared with radio telescopes, results in limited sensitivity when it is used as a radio telescope, the modified system offers advantages over traditional radio telescopes in terms of its flexibility and abundant observation times, and covers observation frequencies that are currently unavailable with other telescopes. After modification, the system can provide value in its ability to monitor certain strong radio sources.

This paper reports on the modification of the distributed Earth-based radar prototype systems for radio astronomical observations and describes the pulsar observation experiment conducted using one of the radar units for approximately 1 h. Section 2 presents a detailed description of the distributed Earth-based radar prototype system used in the experiments, with particular highlighting of the differences between radar and radio telescopes. Section 3 covers the modifications made, the data acquisition backend, and the data processing steps. Section 4 presents the results from the pulsar observation experiment and discusses the feasibility and the limitations of the use of radar systems for radio astronomical observations. Section 5 concludes the paper with a summary of the results.

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2. Distributed Earth-based Radar

Traditional centralized Earth-based deep space radar systems face physical limitations in terms of both their aperture size and their transmission power. Distributed aperture deep space radar systems overcome these constraints by coordinating multiple radar units to realize precise electromagnetic wave focusing at extremely long distances, thus enabling coherent summation and synchronized reception. This approach enhances the signal-to-noise ratio of the received echoes significantly. To validate the feasibility of the proposed distributed aperture deep space radar architecture and to gain experience in the construction of large-scale distributed radar systems while also mitigating potential risks, a scaled-down prototype system[15] was constructed in 2022 at Mingyue Mountain in Liangjiang New Area, Chongqing.

The scaled-down ground-based astronomical radar demonstration and verification system comprises one control center and four distributed active transmitting and receiving antennas, as illustrated in Fig. 1 [Figure 1: see original paper]. Each antenna has a diameter of 16 m, and each radar unit is equipped with independent transmission and reception systems. The central unit is located on the antenna platform and includes the transmitter, the receiver, the optical terminal, the liquid cooling system, the air conditioning system, and the power supply unit. The excitation signal generation and frequency synthesizer equipment, the radar control system, the time-frequency distribution equipment, and the signal processing GPU are housed in the control center, with all signals transmitted via optical fibers.

Unlike radio telescopes, radar systems operate under high-power transmission conditions. To ensure their safety, a control switch is installed after the feed network. This switch operates according to predefined parameters in the configuration file to ensure regulated shutdowns. Fig. 2 [Figure 2: see original paper] presents the system block diagram for the antenna and the central unit.

3. Observation Processing

The distributed radar system is a single-station system and each system antenna must be able to receive and transmit simultaneously. The antenna reflector and the feed network are shared by both the receiving and transmitting functions, and the received and transmitted signals are processed in a time-division manner. The receiving component is a room-temperature S-band single-polarization receiver that offers a best-in-class noise performance. However, for transmission and reception multiplexing and to protect the receiving system, additional microwave devices are added that bring insertion losses and increase the system noise. Nevertheless, the analog receiving part of the system is still able to perform some astronomical observations.

In addition, because the radar signal is usually designed at a fixed frequency, although the front-end analog receiving system can process wider signal ranges, the digital part of the system has a highly targeted design for radar signals and cannot process broader astronomical signals. This system is designed to work with a maximum instantaneous bandwidth of 20 MHz and does not differentiate between frequency channels, which does not meet the requirements for astronomical observation. To enable reception of the astronomical signals, we have modified the entire system based on the principle of minimum modification for validation purposes, with our main focus on the following components:

(1) The time-division modulation process used for receiving system protection was turned off to ensure the continuous operation of the antenna’ s analog receiving system.

(2) The reception capacity of the analog receiving system was re-measured to determine the effective bandwidth that can actually be used to perform astronomical observations. When compared with the original radar system, the receiving bandwidth has been improved significantly, although it remains limited from an astronomical perspective. Through observation

of the radio source calibration process, we determined that the effective output range of the RF system can reach 70 MHz.

(3) A digital signal processing backend[16],[17] dedicated to astronomical observation applications is used to measure the broadband spectrum and record the required data in real time. This backend was developed by the National Astronomical Observatories, Chinese Academy of Sciences (NAOC) and is used to perform multi-antenna broadband pulsar and radio source observations. During observations, we connected the backend to the intermediate frequency/RF output of the analog system, and the backend then digitized the RF signal and performed spectrum measurements before finally saving the results as standard scientific data.

We used the equipment described above to conduct observations, measuring the signal with a total bandwidth of 70 MHz in 141 frequency channels every 48 μs.

The radiation intensity of a pulsar generally follows a power law, and the pulsar's flux density decreases as the operating frequency increases. Pulsar observations in the S-band are significantly fewer than those in the L-band and at lower frequencies. Additionally, many of these observations are completed by deep space antennas operating at approximately 2.5 GHz. There have been only a few observations and flux density measurements in the high S-band. Observations in this band have certain uncertainties because of the limited system sensitivity. Taking the pulsar intensity, the spectral index, and previous high-frequency observations into account, we decided to observe B0329+54, a very bright pulsar in the northern sky.

The observation of PSR B0329+54, which lasted for 60 min, was conducted on October 19, 2024, beginning at 04:20 Beijing time, using Antenna C at Mingyue Mountain. The observational data were recorded in search mode with a time resolution of 48 μs, with a single polarization channel being captured. Data processing was conducted using the DSPSR software package[18]. The pulsar ephemeris, including the dispersion measure ($\mathrm{DM} = 26.76\ \mathrm{pc\ cm^{-3}}$) and the rotational period ($P = 0.71452$ s), was retrieved from the ATNF Pulsar Catalogue[19]. The raw data were first de-dispersed using the specified DM, followed by phase folding at the given period. As a result of the seclusion of Mingyue Mountain from urban areas, RF interference (RFI) within the observation frequency range is virtually nonexistent. Despite maintaining the RFI mitigation measure in the pipeline, there is virtually no difference when compared with not conducting any mitigation at all.

Given the system' s sensitivity and dispersion delay within this frequency band, we combined the frequency channels into 47 channels and merged each rotation period into 128 bins to realize a better signal-to-noise ratio for the pulse-averaged profile which is showed in Fig. 3 [Figure 3: see original paper]. The pulse profile of B0329+54 shows five highly distinguishable components[20–22], but because of the limited number of bins, the components in the integrated profile could not be distinguished clearly using our data.

4. Discussion and Limitations

The second limitation is the observation bandwidth. When compared with the broadband or even ultra-wideband reception required to perform radio astronomical observations, radar astronomy typically operates within a much narrower bandwidth. However, the design of the radar antenna and the feed network systems often retains the potential for a greater bandwidth. This provides the opportunity to extend the bandwidth to some degree at different stages during the radio astronomy adaptation process.

The third limitation concerns the noise from the electronic components used in the system. Radio astronomy deals with extremely weak signals that are highly susceptible to system noise. The design of the low-noise amplifier (LNA) and the front-end receiver microwave network is optimized with sensitivity as its highest priority. In contrast, for functions such as reception and transmission sharing and device protection, radar systems must make compromises in their design that make it difficult to achieve extremely high sensitivity. For example, in this experiment, this part of the design contributed more than half of the total receiver noise temperature, which degraded its capacity for radio astronomy observation significantly.

Modifying an existing radar system to perform radio astronomy observations is feasible, but the quality of the data acquired is generally lower than that which would be obtained if the system had been initially designed with radio astronomy requirements in mind. Given the different requirements of radio astronomy and radar systems, retrofitting a radar system for astronomical use often results in compromised system performance. For future Earth-based radar systems intended to perform both radar and radio astronomy applications, it is important to incorporate the radio astronomy requirements in the design from the outset to achieve optimal efficiency.

One of the main challenges in converting an Earth-based radar system into a radio telescope lies in the discrepancy between the operating frequencies and the optimal observational frequencies that are required for specific astronomical targets. For example, pulsars are typically observed within the frequency range from several hundred megahertz up to approximately 1 GHz, where they emit strong radiation because of their steep spectral index. In contrast, radar systems generally operate at higher frequencies, e.g., the S-band and the X-band. Although these bands are commonly used in radio astronomy, they may exhibit lower sensitivity for observations of pulsars. Additionally, adjustment of the receiving frequency to be more suitable for pulsar observations presents technical challenges and may compromise the radar system’ s original functionality. Therefore, while the S/X-bands and even higher frequencies are suitable for certain astronomical targets, the use of higher frequencies imposes greater demands on the instrument’ s sensitivity when observing radio sources with steep spectral indices, e.g., pulsars.

5. Conclusion

We report an astronomical observation conducted using an Earth-based deep space radar system, thus demonstrating the feasibility of performing astronomical observations without interfering with the radar system' s routine operations. With minimal modifications to the existing system, we successfully observed a pulsar, which is a type of relatively faint celestial object. This observation also implied the potential capacity of the system to perform time domain radio astronomy, for which a large fraction of usable time is available. However, there are also significant deficiencies in the radar prototype system for astronomical use.

This study discusses the limitations and the potential challenges of such an approach, including constraints related to the radar design, the receiving frequency, the bandwidth, and the noise introduced by the radar-specific receiver design. The lessons learned in this work provide valuable insights for the adaptation of existing radar systems for use in radio astronomical observations. Furthermore, we offer recommendations for the integration of astronomical observation capabilities into future large-scale radar systems.

Although the prototype system' s sensitivity is limited, its flexible and abundant observation time, along with its unique observation frequency range, which is not covered by other telescopes, highlights the potential value of the proposed modified radar-based radio astronomy telescope for monitoring strong radio sources.

The datasets generated and analyzed during the current study are not publicly available. However, they are available from the corresponding author upon reasonable request.

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AI DISCLOSURE STATEMENT

DeepL and ChatGPT-3.5 were employed for language and grammar checks during the preparation of the manuscript. The authors thoroughly reviewed and edited all AI-generated suggestions, and assume full responsibility for the final content of the publication.

AUTHOR CONTRIBUTIONS

Xue Chen completed commissioning observation, the data processing, and manuscript writing for the paper. Yuyang Ma collected materials and assisted with the observations. Xiaoyun Ma set up the astronomical observation system up and performed commissioning observation and manuscript writing. Junjie Huang helped generate the observation files. Zehua Dong and Zegang Ding served as the project leaders and reviewed the manuscript. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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