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The Partial Process, Principles, and Related Specific Cases of Detecting Celestial Objects in the Universe Using Radio Telescopes

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Abstract. Radio astronomy reveals a universe beyond the visible light spectrum by detecting radio waves emitted by celestial objects, uncovering unique phenomena such as pulsars, interstellar molecules, and active galactic nuclei. Central to this field is the use of radio telescopes to capture, amplify, and analyze faint cosmic radio signals, a process involving intricate signal collection, interferometry, and data processing techniques. Understanding these principles and analyzing the design, performance, and scientific output of globally representative radio telescopes is crucial for evaluating current observational capabilities and guiding future advancements. The main research contents of this paper include the analysis of the parabolic surface, feed source, Analog-to-Digital Converter, the hydrogen 21cm line, Doppler effect in radio telescope, as well as specific studies on two radio telescopes—the Parkes Radio Telescope and the Australia Telescope Compact Array. The research objective of this paper is to integrate the scattered research findings and theoretical principles in this field, analyze existing achievements, and propose projections for future developments in this domain. Based on a review of relevant literature, this study employed methodologies including literature analysis, case studies, and a comprehensive review. It outlines fundamental principles and processes relevant to radio telescopes and analyzes two specific cases. Future perspectives for advancements in this field are also proposed.

Keywords: Radio Telescopes, Reflector Antennas, Analog-to-Digital Converter, Hydrogen 21cm Line, Doppler Effect

1. Introduction

Radio telescopes, designed to detect celestial radio emissions, have revolutionized people's understanding of the universe since Karl Jansky's discovery of Galactic center radiation in 1932. Unlike optical instruments, they capture faint radio waves generated by cosmic phenomena—from pulsar rotations to interstellar molecular transitions—enabling studies of invisible astrophysical processes. The core workflow involves three stages:

a. Signal collection via parabolic reflectors (e.g., FAST's 500-meter dish focusing waves onto a feed cabin);

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b. Amplification and conversion by cryogenically cooled receivers to minimize noise, transforming electromagnetic waves into electrical signals ;

c. Data processing using digital backends for spectral or temporal analysis, extracting physical properties like distance and composition.

Modern facilities such as China's FAST (Five-hundred-meter Aperture Spherical Telescope) exemplify technological leaps. With sensitivity 10× higher than the Arecibo telescope, FAST has detected over 509 pulsars and distant fast radio bursts (FRBs), probing cosmic structure and dark matter. Future advancements like the Square Kilometre Array (SKA) will further enhance multiband synergy, driving explorations into the early universe and potential technosignatures. This paper details the operational principles and observational pipeline of radio astronomy, highlighting its indispensable role in decoding the cosmos.

2. Working principle of radio telescope

2.1. Reflector antennas

Reflector antenna (see Figure 1) is a high-gain device that uses metallic reflectors to direct electromagnetic waves, consisting of a reflector and a feed. Its operation relies on geometric optics: spherical waves from the feed are converted into planar waves by the reflector (transmit mode), or incoming waves are focused onto the feed (receive mode) [1,2]. Common types include:

a. Single-reflector antennas: Parabolic reflectors (e.g., FAST telescope) are widely used in satellite communications.

b. Dual-reflector antennas: Cassegrain (hyperbolic sub-reflector) and Gregorian (elliptical sub-reflector) antennas reduce feed blockage via secondary reflection.

c. Offset-fed antennas: The feed is offset from the reflector axis to avoid blockage, ideal for automotive radars.

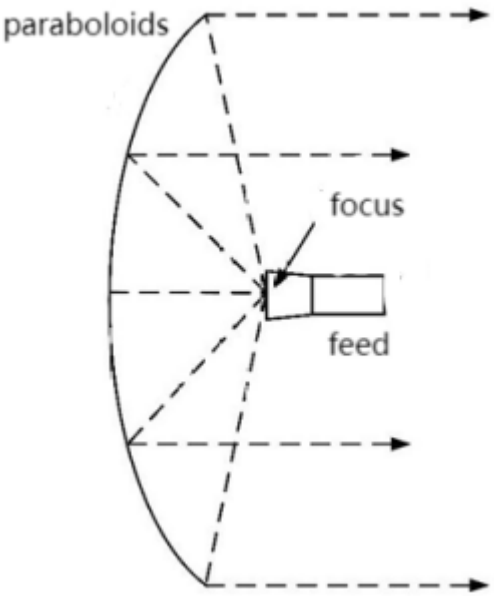


Figure 1. Reflector antenna [2]

Key performance parameters are gain, beamwidth, and efficiency. Here is the gain formula:

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$$D = \frac{4\pi A}{\lambda^2}\eta_A \tag{1}$$

The gain formula indicates dependence on aperture area A, wavelength λ, and efficiency η. Losses arise from surface inaccuracies, feed spillover, and edge diffraction.

Reflector antennas have a wide range of applications, including satellite communications, where Cassegrain antennas enable high-speed data links between ground stations and GEO satellites; radio astronomy, where parabolic reflectors detect the 21 cm hydrogen line to map cosmic structure; and radar systems, where offset reflectors achieve low sidelobes for precise target tracking. To detect stars in space using the 21 cm spectrum, a parabolic antenna must first collect the signal and then reflect it back to the feed.

2.2. Working principle of paraboloids

The basic shape of a parabolic antenna is similar to that of a satellite TV receiver. Its special curved surface reflects parallel radio waves to a single focus, similar to the reflector bowl of a flashlight that focuses light. Mathematically, an ideal parabolic surface satisfies the equation:

$$y^2 = 4Fz \tag{2}$$

Where F is the focal length. When radio waves are incident parallel to the main axis of the paraboloid, all reflected waves converge at the focal point. Paraboloid has the following key characteristics:

Gain enhancement: the larger the diameter, the more radio waves are collected. An antenna with a diameter of 50 meters is 25 times stronger than an antenna with a diameter of 10 meters in signal reception.

b. Directionality: A pencil-shaped beam is generated, and the width of the beam is determined by the wavelength/diameter (for example, a 30-meter antenna for a 1GHz radio wave has a beam width of about 0.7 degrees).

2.3. The function of the feed source

The feed source is a metal horn structure installed at the focal point, which has the following main functions:

Signal conversion: The converging electromagnetic wave is converted into the current signal in the cable.

b. Low noise reception: Cosmic signals are extremely weak (e.g., neutral hydrogen 21cm spectral line), and the feed source needs to be integrated with a cryogenic cooling system (-263 C) to reduce thermal noise (e.g., FAST's 19-beam feed source).

c. Multi-beam scanning: The array feed can form multiple beams at the same time to improve the sky survey efficiency (for example, FAST covers 19 sky areas in a single observation).

Common feed types include the cone horn, which is suitable for the 1–10 GHz frequency band, and the ripple horn, which improves the uniformity of signal reception across different frequencies through its internal groove design.

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2.4. Analog-to-Digital Converter(ADC)

In radio astronomy systems, signals from cosmic sources are initially analog signals—continuous voltage waveforms varying with time, generated by receivers converting captured electromagnetic waves. These analog outputs contain critical information about celestial objects but are vulnerable to noise degradation during transmission [3].

Digital signals, in contrast, represent data as discrete binary sequences (0s and 1s). Their noise immunity, storage efficiency, and compatibility with computational processing make them essential for modern astrophysical analysis.

The Analog-to-Digital Converter (ADC) bridges this transition (see Figure 2). It samples analog voltages at fixed intervals (e.g., GHz rates for pulsar observations) and quantizes amplitudes into digital values. For telescopes like FAST or SKA, ADCs enable:

Long-term data preservation (digital formats resist degradation);

High-speed signal processing (e.g., Fourier transforms for spectral line extraction);

Multi-beam synthesis (simultaneous digitization of array feeds).

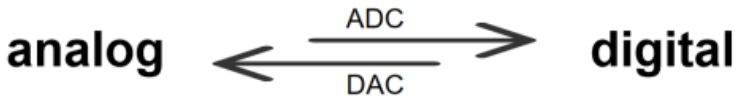


Figure 2. Signal conversion

Without ADCs, real-time analysis of weak cosmic signals (e.g., 21 cm HI lines) would be infeasible.

3. How radio telescopes detect celestial bodies

3.1. The hydrogen 21cm line

The 21cm hyperfine transition line(see Figure 3) of neutral hydrogen (HI) arises from the spin-flip interaction between the proton and electron in the ground state, emitting radiation at a wavelength of 21cm (1.42 GHz). Predicted theoretically by H.C. van de Hulst in 1944 and first observed in 1951, this line serves as a unique probe of cosmic neutral hydrogen due to its ability to penetrate interstellar dust. Doppler shifts in the line trace galactic dynamics, while cosmological redshifts map large-scale structure formation. Modern radio telescopes (e.g., FAST, SKA) utilize this line to study dark matter distribution and the epoch of reionization. Challenges include isolating the weak signal from foreground radiation, driving advancements in low-frequency radio astronomy [4,5].

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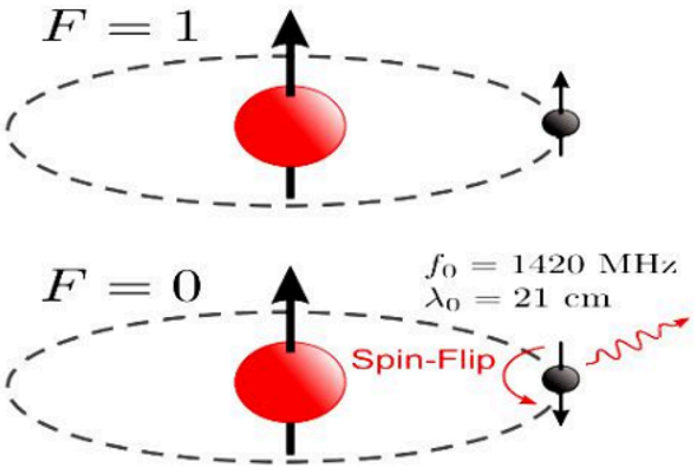


Figure 3. The principle of the neutral hydrogen 21 cm line [4]

3.2. Doppler effect

The Doppler effect describes the change in frequency or wavelength of a wave due to relative motion between a source and an observer. For electromagnetic waves (e.g., light), when a celestial object moves away from Earth, its spectral lines shift toward longer wavelengths (redshift); conversely, approaching motion causes blueshift39. In astronomy, this principle enables velocity measurements [6]:

Redshift(z) is quantified as $z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}}$, where λ_{rest} is the laboratory-measured wavelength.

Hubble's Law links redshift to cosmic expansion: $v = H_0 \times d$, with v being recession velocity, H_0 the Hubble constant, and d the distance.

The applications of Doppler effect include that: Measuring rotation curves of galaxies to infer dark matter distribution, identifying stellar "wobbles" via periodic redshift/blueshift variations, and confirming universe acceleration using Type la supernovae redshifts (which won the Nobel Prize in 2011).

We need to note that cosmological redshifts are due to the expansion of space itself, not the movement of celestial bodies in space. While redshift reveals motion, its evolution over time is captured in time-frequency plots, essential for transient events like pulsars or FRBs.

4. Some examples about radio telescopes

4.1. Parkes radio telescope

The Parkes 64-meter radio telescope, commissioned in 1961, is renowned for its pivotal role in lunar missions and pulsar astronomy. It gained global recognition during the 1969 Apollo 11 mission by relaying live television signals of the moonwalk [7]. Its recent support for the Odysseus lunar lander (February 2024) exemplifies its enduring capability: when the lander's antenna failed, Parkes detected faint signals (1.4-1.7 GHz) from the Moon's south pole, enabling data recovery through high-sensitivity beamforming.

Parkes is instrumental in studying fast radio bursts (FRBs) and pulsars, connecting directly to time-frequency analysis and Doppler effects: Perytons RFI Resolution: Parkes once detected "perytons"—dispersive signals mimicking FRBs. Research revealed these originated from

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microwave oven emissions during door-opening events (2.3-2.5 GHz), resolved via out-of-band signal analysis [8]. This underscores the importance of RFI mitigation in ADC systems (as discussed in Section 2.4).

Project P1336 (2024-2025) uses Parkes' Ultra Wide Low Band (UWL) receiver to search for pulsars near the Galactic Center. Scattering from interstellar dust broadens pulses at low frequencies, but UWL's broadband coverage (704-4032 MHz) compensates via coherent dedispersion, aligning with Doppler-based velocity measurements of binary systems.

The Parkes Radio Telescope (Murriyang) has driven significant advances through innovations like its real-time RFI (Radio Frequency Interference) cancellation system. Developed collaboratively with Chinese astronomical institutions including Xinjiang Observatory, this GPU-accelerated platform suppresses interference in ultra-wideband (UWL) data, crucially enhancing signal integrity for detecting faint high-redshift fast radio bursts (FRBs). Critical RFI characterization methodologies were established in the seminal study by Petroff et al. (2015, MNRAS 451:3933) - which has garnered over 300 citations - detailing the identification of terrestrial RFI sources at Parkes [8]. Key technical parameters underpinning these capabilities include: a 64-meter diameter primary reflector, a UWL receiver covering 0.7-4 GHz, and an angular resolution of 12 arcminutes at 1.4 GHz. These specifications enable flagship projects spanning FRB detection, precision pulsar timing arrays, and lunar mission support.

4.2. Australia telescope compact array

Located in Narrabri, Australia, the ATCA features six 22-meter antennas movable along a 6-kilometer rail track, achieving interferometric resolutions as sharp as 0.8 arcseconds at 10 GHz. Its distinct advantage lies in unparalleled southern-sky coverage (declination < −30°), essential to studying the Galactic Center and proximate galaxies like Centaurus A—targets inaccessible to northern hemisphere facilities such as the VLA. The array's spectral-line capabilities directly leverage Doppler principles: in galactic dynamics, HI 21-cm line mapping of the Large Magellanic Cloud (LMC) resolved velocity gradients ($\Delta v > 50$ km/s) indicative of dark matter halos through Fourier-transform spectrometer processing. For transient follow-up, ATCA coordinates with the Parkes telescope via Very Long Baseline Interferometry (VLBI), exemplified by its sub-arcsecond localization of FRB 180924 in 2020. Combined with Parkes' dispersion measures, this confirmed the burst's extragalactic origin ($z = 0.32$). Key technical parameters include reconfigurable antenna positioning, frequency coverage spanning 3 mm-21 cm (including W-band: 84-116 GHz), a maximum 6-km baseline (extendable to >300 km with Parkes for VLBI), and milliarcsecond-scale resolution at high frequencies.

As a cornerstone facility for southern hemisphere radio astronomy, the Australia Telescope Compact Array (ATCA) deciphers cosmic phenomena through precision interferometry. Its observational workflow initiates with parabolic reflectors concentrating celestial radio emissions onto cryogenically stabilized feeds that generate low-noise analog signals. These outputs undergo quantization via high-speed analog-to-digital converters, enabling robust noise suppression critical for broadband signal processing across millimeter to centimeter wavelengths. Subsequent Doppler analysis leverages spectral redshift measurements ($z = \Delta\lambda/\lambda$) to reconstruct kinematic profiles, while time-frequency decomposition through dynamic spectroscopy resolves transient behaviors. For cosmological interpretation, ATCA complements large-scale redshift surveys by mapping three-dimensional matter distributions, where baryon acoustic oscillation signatures constrain dark energy models. This integrated pipeline—from photon capture to cosmological inference—exemplifies how

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advanced instrumentation transforms electromagnetic emissions into fundamental astrophysical insights.

Case studies of Parkes and ATCA exemplify this synergy: Parkes' UWL receiver advances pulsar timing through real-time RFI suppression, validating gravitational wave models. ATCA's interferometric imaging of HI kinematics in the LMC quantifies dark matter halos using Doppler-broadened line profiles. Future facilities like the SKA will unify high-sensitivity detection with milliarcsecond VLBI, probing cosmic dawn through 21 cm tomography.

5. Conclusion

Radio astronomy deciphers the cosmos by capturing celestial radio emissions through reflector antennas, where parabolic dishes focus waves onto cryogenically cooled feeds to generate analog signals. These signals undergo digitization via high-speed ADCs—such as FAST's 19-beam array sampling at 200 Gbps—enabling noise-resistant processing for spectral and temporal analysis. Doppler principles are pivotal here: spectral redshifts ($z=\Delta\lambda/\lambda$) trace kinematic motions, while dynamic spectrograms resolve transient evolution, exemplified by Parkes Telescope's detection of frequency-drifting pulses from FRB 121102. This end-to-end workflow finds practical validation in iconic facilities: Parkes advances pulsar timing through real-time RFI suppression, directly confirming gravitational wave models; simultaneously, ATCA's interferometric imaging quantifies dark matter halos in the Large Magellanic Cloud by analyzing Doppler-broadened HI line profiles. Future telescopes like the SKA will unify these capabilities, leveraging milliarcsecond-resolution VLBI and high-sensitivity arrays to probe cosmic dawn.

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