Chapter 2
Fundamentals of a Radio Telescope

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ABSTRACT

In radio astronomy, radio telescopes are used to collect radio waves emanated from cosmic sources. By analyzing these signals, the properties of the sources could be unraveled. A telescope typically consists of the following astronomical instruments: a primary and a secondary reflector, receiver optics which usually includes a lens or a pair of mirrors and a pair of feed horns (one for each orthogonal polarization [or simply a corrugated horn with an orthomode transducer OMT]), waveguides, a mixer circuit, a local oscillator, amplifiers, a detector circuit, and a data processing unit. This chapter provides a concise but complete overview of the working principle of the astronomical instruments involved in the construction of a radio telescope. The underlying physics of the components in a radio telescope, ranging from the antenna to the front-end and back-end systems, are illustrated.

INTRODUCTION

In radio astronomy, radio telescopes are built to observe naturally occurring signal emission from celestial objects and phenomena, such as stars, galaxies, planets, quasars, pulsars, active galactic nuclei (AGN), etc. Extraterrestrial signals within the radio wave regime are rich with spectral and spatial information which is important in the field of astrophysics. By analyzing these signals, knowledge about the universe, as a whole, and a specific cosmic source, in particular, could be unraveled. The signal emission detected from the dust clouds in the interstellar medium (ISM), for instance, allows astrophysicists to study the physical and chemical properties during the formation of a star. Similarly, the Cosmic Microwave Back-

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ground (CMB) radiation provides information of the early universe when it was approximately 375,000 years old. It also reveals the age and composition of the universe.

The latest generation of radio telescopes, such as those being employed in the Atacama Large Millimeter/submillimeter Aray (ALMA) and Square Kilometer Array (SKA) projects, are designed for multiple frequency bands with receivers for each individual band offset from the antenna axis. These telescopes typically consists of the following astronomical instruments: a primary and a secondary reflector, receiver optics which usually includes a lens or a pair of mirrors and a pair of feed horns (one for each orthogonal polarization) (Yeap & Tham, 2018), waveguides, a mixer circuit, a local oscillator, amplifiers, a detector circuit, and a data processing unit. These components are summarized in the functional block diagram depicted in Figure 1. To understand the process how a radio telescope detects and interpret the signal emanated from a celestial object, one can imagine the electromagnetic energy propagates from a far-field radio source. When the beam, in the form of a collimated bundle of radio waves, is incident upon the primary reflector of the dish antenna, it is scattered to the secondary reflector. The secondary reflector, in turn, illuminates the first and then the second mirrors (assuming that the focusing elements in the receiver optics are a pair of mirrors). The radio frequency (RF) signal is eventually focused to a feed antenna, which is usually a horn. At the feed, the RF signal is directed, via waveguides, to a receiver circuit. The mixer circuit at the receiver modulates the RF signal with another signal generated by a local oscillator. The process of modulation down converts the signal to an intermediate frequency (IF) signal, while maintaining its original phase. This IF signal is then fed to a detector circuit after going through amplification. The purpose of the detector is to perform wave rectification, allowing it to be processed by a data processing unit. In general, the input signal from the reflector antennas undergoes two stages, namely, the frond-end and the back-end. The components from the receiver optics to the mixer are considered as part of the front-end system; whereas, those from the amplifier to the data processing unit (which includes both the computer and display) belong to the back-end system. In this chapter, the astronomical instruments involved in the construction of the radio telescope, ranging from the parabolic dish antenna to the front-end and back-end components will be illustrated.

REFLECTOR ANTENNAS

Due to its large collecting areas and relatively high angular resolution over a wide frequency range, circular parabolic reflector antennas are commonly employed in radio telescopes. According to the theory of reciprocity, when a beam of collimated rays is incident upon a parabolic reflector, it will converge to a focal point; and, likewise, when a point source is placed at the focal point, the rays scattered from the reflector will emerge as a collimated beam (Balanis, 2005). Although the purpose of the antenna is to collect radio signals from distant celestial sources, the opposite approach is usually adopted when designing a radio telescope. Since the location among different sources may vary, it is, therefore, more convenient to assume that the antenna is transmitting rather than receiving during its design stage.

Various geometrical configurations exist in the design of reflector antennas. The most common types are the Cassegrain, Gregorian, and prime focus designs. Figures 2 to 6 show the optical arrangement for these three types of design. The design of the prime focus (which is also known as the front-fed) is the simplest. It comprises only a single primary reflector, with a feed antenna mounted directly at the focal point. The aperture of the feed is facing downwards towards the reflector dish. The Cassegrain and Gregorian antennas, on the other hand, are multiple-reflector antennas, i.e. they consist of at least two

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